FACTORS LEADING TO STRUCTURE LOSS ON THE THOMAS FIRE

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ABSTRACT

Factors Leading to Structure Loss on the Thomas Fire

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The recent surge in fire activity and the extent of displaced communities as a result of wildfire has increased awareness of wildfire issues nationwide (Syphard et al., 2017). Climate change, population growth, and continued development in the wildland urban interface (WUI) has contributed to a growing body of research into the underlying causes of this continued destruction (Kramer et al., 2019). There is no doubt that statewide policies, such as defensible space or building regulations, are associated with home survival (Keeley & Syphard, 2019). However, the relative effectiveness of wildfire mitigation depends on a myriad of factors specific to individual communities impacted by wildfire. This study focuses on factors that contributed to structure loss as a result of the 2017 Thomas Fire in Ventura, CA. Through spatial analysis utilizing GIS software, we were able to determine that defensible space played a minimal role in structural survivability during the Thomas Fire. Our research shows that fence type (noncombustible, combustible, or none) is a more significant factor at decreasing the odds of structure loss for homes experiencing wildfire under similar conditions. Effective wildfire mitigation relies on multiple factors, and government agencies must take a holistic approach rather than singular, "one size fits all" approaches to reduce the impact of future catastrophic wildfire.

Keywords: WUI, wildfire, wildland urban interface, Thomas Fire, Structure loss, wildfire mitigation

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. **INTRODUCTION**

The recent surge in fire activity and the extent of displaced communities as a result of wildfire has increased awareness of wildfire issues nationwide (Syphard et al., 2017). California has experienced record-breaking wildfires, both in size and destructiveness, for three years in a row (“Cal Fire Stats & Events,” 2018). The 2018 Mendocino Complex, which consumed nearly 460,000 acres, was the largest recorded wildfire while the 2018 Camp Fire, responsible for 85 deaths (“Facts + Statistics: Wildfires | III,” 2019), was the deadliest recorded fire in CA history. Future modeling projections related to the impacts of wildfire suggest a worsening problem, both in CA and nationwide.

Climate change, population growth, and continued development in the wildland urban interface (WUI) has contributed to a growing body of research into the underlying causes of this continued destruction (Kramer et al., 2019). Wildfire ignitions are exceedingly human-caused; in fact, the Department of the Interior (DOI) reports that ninety percent of wildfires are human-caused (“Facts + Statistics: Wildfires | III,” 2019). Nevertheless, current efforts to mitigate the impacts of increased fire activity are not proving effective at preventing structure loss (Kramer et al., 2019). Traditional mitigation techniques, such as defensible space, have failed to yield positive results during extreme CA wind events, such as the Santa Anas (Keeley & Syphard, 2019).

The focus of this study is the 2017 Thomas fire in Ventura County, CA, which damaged or destroyed 1,343 structures, was the direct cause of two fatalities, and, at the time, was the most destructive wildfire in California history. Fueled by strong Santa Ana winds, the Thomas fire consumed over 118,000 acres and hundreds of homes within the first 48 hours (Nauslar et al., 2018). This damage occurred despite an aggressive, mandated vegetation management (defensible space) program and homes constructed with fire-resistant building materials. This research asks what role did defensible space and building materials play in promoting structural survivability during the 2017 Thomas Fire? Are there other confounding variables at play within the WUI that make current mitigation methods less effective at reducing risk?

This study aims to assess the effectiveness of defensible space and other structural variables on home loss as a result of the 2017 Thomas Fire. By comparing neighboring homes, burned against unburned, it will be possible to conclude if pre-fire mitigation played a role in predicting home loss. By using Geographical Information Systems (GIS) software, statistical modeling, and Google Earth Streetview, we conclude that current statewide, blanket policies are ineffective at predicting home survival. Mitigation strategies should be developed to reflect the community in which they are to be implemented. Thus, this study reveals that homes exposed to wildfire under similar weather conditions, have similar topography, and have a similar home design to those sampled on the Thomas fire require different techniques to decrease structure loss during a wildfire.

Figure 1 Location of the 2017 Thomas Fire in California

1.1. Statement of the Problem

In the last decade, wildfires across the US have destroyed tens of thousands of homes and caused hundreds of deaths (Syphard et al., 2014). Years of prolonged drought, climate change, a buildup of vegetative fuels, and the expansion of the Wildland Urban Interface (WUI) have made conditions in California especially vulnerable to catastrophic wildfires (Nauslar et al., 2018). As a result of increased fire activity and destruction over the last decade, a flood of mitigation policies and building standards have been implemented throughout California (Kramer et al., 2019). However, there is little empirical evidence to demonstrate the relative effectiveness of these policies on preventing home loss during wildfires (Syphard et al., 2017).

As such, policies instituted on a macro scale disregard the subtler spatial and temporal differences present in each landscape that dictate fire behavior and determine the effectiveness of specific mitigation strategies. Homeowners, for example, may benefit from upgrading a fence or their windows rather than spending money on defensible space. Thus, there is a need to understand the relative effectiveness of current mitigation strategies and to provide homeowners with realistic goals to reduce their risk.

1.2. Research Questions

1. Was defensible space a factor in preventing structure loss as a result of the 2017 Thomas Fire?
2. What overarching factors resulted in structure loss during the Thomas Fire?
3. What are effective strategies for promoting structural survivability during a wildfire?

1.3. Purpose of the Study

The focus of this research applies to the 2017 Thomas Fire in Southern California. However, within the context of wildfire mitigation, the results of this study can be applied worldwide. In order to reduce the impacts of wildfires on human developments, it is imperative that fire and land managers, develop appropriate and effective mitigation strategies that consider local factors rather than a "one size fits all" approach. Through spatial analysis utilizing GIS software, we were able to determine whether defensible space was a factor in home survival and the impacts of fence type on structural survivability.

1.4. Definitions of Terms

- WUI (Wildland Urban Interface)- The Wildland Urban Interface community exists where humans and their development meet or intermix with wildland fuel (*Federal Register :: Urban Wildland Interface Communities Within the Vicinity of Federal Lands That Are at High Risk From Wildfire*, 2016)
- NIST (National Institute of Standards and Technology) -The mission of NIST is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life (National Institute of Standards and Technology, 2010)
- Firewise Community- A Firewise Community is an NFPA program that teaches people how to adapt to living with wildfire and encourages neighbors to work together and take action to prevent losses ("NFPA - Firewise USA®," n.d.).
- NFPA (National Fire Protection Association) – The leading information and knowledge source on fire, electrical, and related hazards ("NFPA," n.d.).

- Defensible Space – A 100-foot buffer of cleared or thinned vegetation from around buildings (or up to the property line) to create a defendable buffer to impede direct flame contact and provide a safe area for suppression resources. (“Fire Safety Laws – Ready for Wildfire,” 2019)
- HIZ (Home Ignition Zone) - The area where the factors that principally determine home ignition potential during extreme wildfire behavior (high fire intensities and burning embers) are present. The characteristics of a home and its immediate surroundings within 100 feet comprise the HIZ (“Home Ignition Zone (HIZ) | NWCG,” 2019)
- PRC (Public Resource Code) – California law relating to natural resources, the conservation, utilization, and supervision thereof, along with mines and mining, oil and gas, and forestry (“California Public Resources Code Statutory History,” 2019).
- SRA (State Responsibility Area) - Land where the State of California is financially responsible for the prevention and suppression of wildfires (Informational Report for State Responsibility Area Prevention, 2017).
- LRA (Local Responsibility Area) – Land where the local municipality is financially responsible for the prevention and suppression of wildfires (Informational Report for State Responsibility Area Prevention, 2017).
- FRA (Federal Responsibility Area) – Land where the federal government is financially responsible for the prevention and suppression of wildfires (Informational Report for State Responsibility Area Prevention, 2017).
- FHSZ (Fire Hazard Severity Zone) - A FHSZ is a mapped area that designates zones (based on factors such as fuel, slope, and fire weather) with varying

degrees of fire hazard (California’s Fire Hazard Severity Zones California Department of Forestry and Fire Protection Office of the State Fire Marshal, 2007)

- ROS (Rate of Spread) - Rate of spread is a measure of the speed of progression of a fire perimeter and can be expressed as the forward, backing, or flanking speed relative to the direction of the prevailing wind driving fire spread (Sullivan & Gould, 2019).

CHAPTER 2. **LITERATURE REVIEW**

The 2017 and 2018 fire seasons were the most deadly and destructive wildfire seasons in California history (“Cal Fire Stats & Events,” 2018). Wildfires continue to break records nationwide; this is especially evident in California, where since 2000, wildfires have broken records, not only in acres burned but in destructiveness, suppression costs, and fatalities (Keeley & Syphard, 2019). The 2018 Mendocino Complex was California’s largest reported wildfire, consuming nearly 460,000 acres and causing one fatality. Theories abound about the cause of increased fire activity, such as prolonged drought, biotic disturbances, increasing development, climate change, and poor land management techniques. Regardless of the cause, however, increased fire activity and incidents of catastrophic wildfires in California are on the rise (Koss et al., 1996).

Despite an influx of new laws and policies developed to help manage the risks associated with wildland fire (Winter et al., 2009), residential losses attributed to wildfires continue to have serious economic, social, and ecological consequences. Historically structure loss as a result of wildfire has been attributed to housing developments near or adjacent to wildland fuels. Wildfire mitigation programs have primarily focused on reducing the number of hazardous fuels surrounding structures. Government agencies have spent billions promoting and conducting fuel reduction treatments; however, suppression costs, fuels treatment costs, and fire activity continue to increase (Syphard et al., 2012). Scientists who study structure loss are starting to realize that fuels treatments are only successful under certain circumstances. Whether a structure will survive a wildfire may be attributed to building materials, location, and land use planning (Syphard et al., 2012). This lack of consensus amongst land and fire managers has left the public confused about the best way for homeowners to protect their homes.

The relationship between humans and wildfire ignitions is evident in areas with high population density. Balch et al. (2017) reported that 84% of the 1.5 million fires between 1992 to 2012 were anthropogenic. In California alone, the 2018 fire season damaged or destroyed nearly twenty thousand structures (“Cal Fire Stats & Events,” 2018). The majority of these wildland fires are started in the Wildland Urban Interface (WUI) in areas with high housing density (Radeloff et al., 2018). Since 1990 60% of new homes nationally have been built in the WUI (Mitigating the Risk of Wildfires in the Wildland-Urban Interface | whitehouse.gov, 2016). Population growth and continued development have increased the number of urban areas considered to be in the WUI. Consequently, this has left California communities at an increased risk of falling victim to the devastating effects of wildfire.

2.1. Southern CA Fire Regimes

Large, destructive wildfires are not new to the California landscape (Nauslar et al., 2018). The Mediterranean climate of California with hot, dry conditions in the summer, coupled with months devoid of precipitation, lends itself to frequent fire events. The abundance of fire-adapted species across the California landscape is further proof that fire has been a part of the California ecosystem for millennia (Sugihara, 1981). While pyrophytic vegetation is uniquely able to withstand long periods of drought, it is also extremely flammable, thus exacerbating the fire problem (Kocher & Butsic, 2017). Southern California is dominated by pyrophytic plant communities, such as chaparral, which burns at high intensity. Chaparral fires tend to receive a lot of media coverage and capture the public’s attention when they burn in urban areas driven by strong winds (Carle, 2008). Seemingly continuous development across the West, especially in California, has turned historically fire-prone and fire resilient landscapes into urban environments.

Individual plant communities are uniquely adapted to their environment. Each ecosystem has evolved to withstand specific climatic conditions and endure the natural disturbances native to their environment. Before European settlement in California, conifer forests had a 10-30-year fire return interval (Carle, 2008), while chaparral dominated landscapes had 60-100 year intervals (Keeley & Fotheringham, 2001). Fire return intervals and natural fire regimes have been impacted by urban sprawl, population growth, and aggressive fire suppression. Wildfire is often portrayed as an unnatural disturbance or a disruption to natural conditions. However, wildfire is an essential component of ecological succession and can be a predictably regular ecological process (Sugihara, 1981).

Typical Southern California fire regimes have seasonal patterns. California fire and land management agencies employ thousands of extra, seasonal personnel to handle the influx of fires during the hot and dry months of summer and fall. However, shortened fire return intervals have altered the structure of native vegetation, which alters fire activity, further affecting the native fire regime.

Increased anthropogenic pressure on chaparral has resulted in a vegetative type conversion from brush to invasive grasslands (Safford, 2007). Annual grasses are considered light, flashy, 1-hour fuels. A 1-hour fuel takes approximately this long to reach ambient atmospheric moisture conditions. This means that it is highly susceptible to diurnal temperature fluctuations and ignites easily during periods of extreme fire weather conditions, common to Southern California. As such, the majority of destructive, large fires have been a result of chaparral fires (Keeley et al., 2004). Often, these fires are ignited in grasslands or along roadsides and quickly transition into chaparral shrub communities and threaten urban developments.

Southern California climate generally results in two distinct types of wildfires; rapidly expanding wind-driven fires (foehn wind events), and non-wind event, fuel driven fires that occur as a result of hot, dry conditions (Jin et al., 2015). Native plant communities and their associated fire regimes have evolved to cope with such wind events. However, urban dwellings are taking the place of plant communities and are being consumed at high numbers as a result of fast-moving wildfires. The buildup of fuel and further urban expansion into the wildland exacerbate the disruption of natural fire regimes. The Thomas fire is a prime example of the collision of fire-prone landscapes and urban development. Heavy fuel loading, fast-moving Santa Ana winds, steep topography, and high-density housing allowed the Thomas fire to consume over 500 homes within the first 48 hours of the fire.

2.2. Historical Large fires in California

California history is littered with massive wildfires; records in destructiveness, size, and cost are broken nearly every fire season. In fact, since the onset of this study, the Thomas fire (Fig. 2) has been surpassed as the largest wildfire in CA history by the 2018 Mendocino Complex, which burned 459,123 acres across four counties, nearly doubling the area burned by the Thomas fire (“Facts + Statistics: Wildfires | III,” 2019). Ventura and Santa Barbara counties, where the Thomas Fire occurred, are home to three of the top ten largest CA wildfires (2007 Zaca Fire, 1932 Matilija Fire, and 2017 Thomas Fire) (“Facts + Statistics: Wildfires | III,” 2019). A Fire Resource and Assessment Program (FRAP) data set compiled by the California Department of Forestry and Fire Protection (Cal Fire) reveals that over half of Ventura and Santa Barbara counties have burned since the 1950s. (Fig. 3)

However, these facts have not decreased the spread of development into fire-prone areas. Increased focus on structure protection has led to fewer resources available to battle wildfires. As more people move to areas designed by nature to burn, land use planning will play a vital role in building fire resiliency. Determining where houses can be built and their arrangement may have more of an impact than trying to exclude fire from the landscape (Kocher & Butsic, 2017).

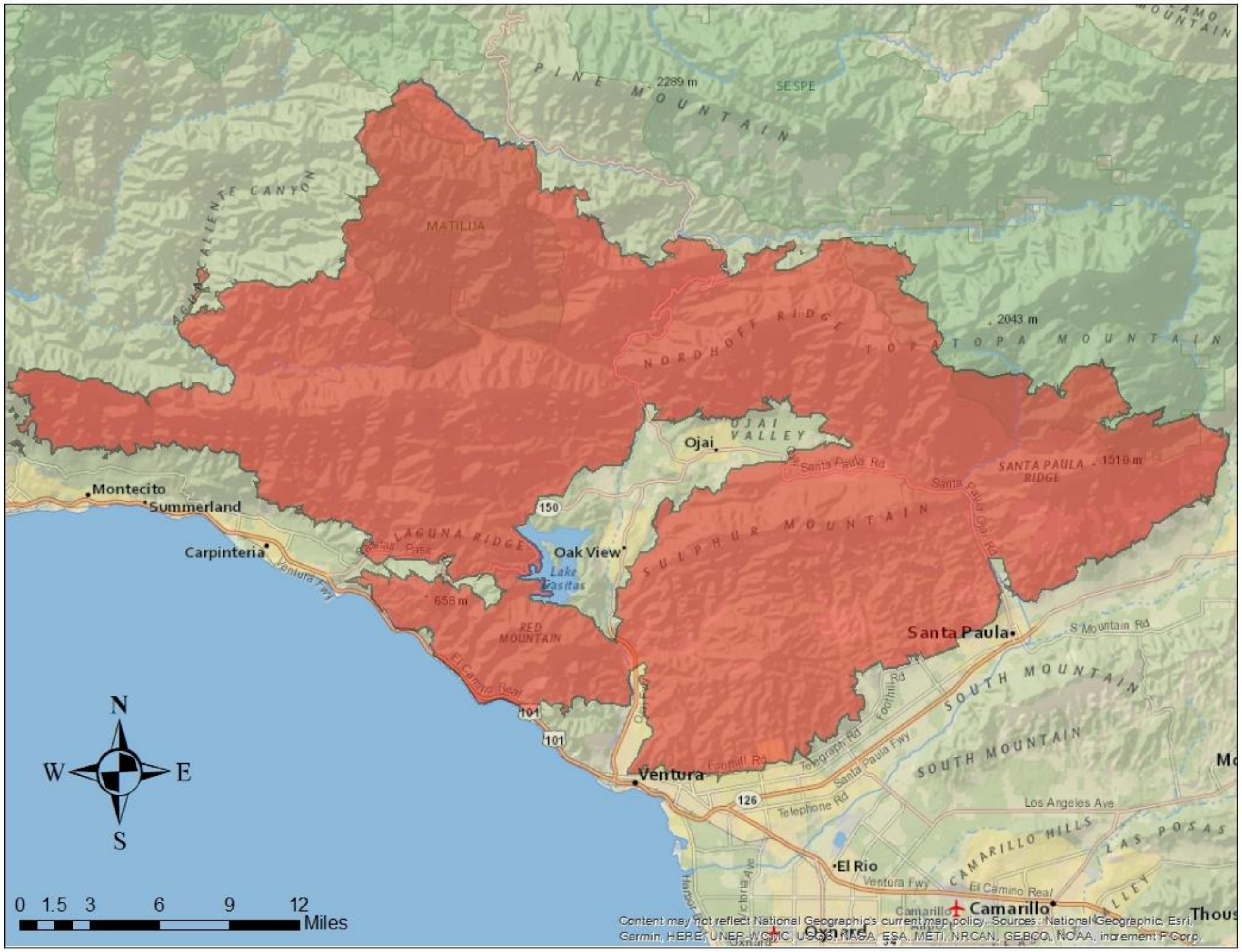


Figure 2 Thomas Fire burn perimeter in Santa Barbra and Ventura Counties

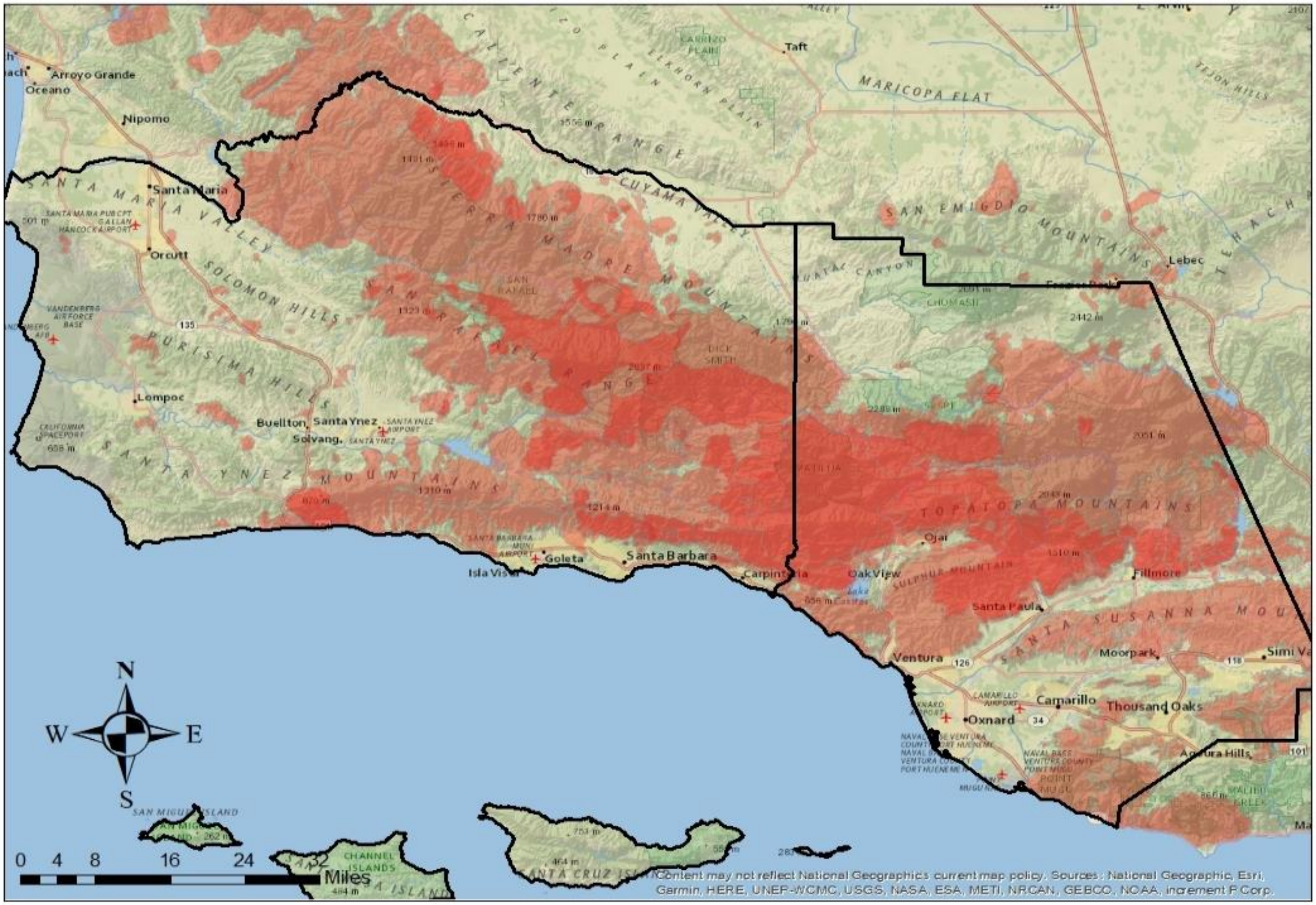


Figure 3 Total area burned across Santa Barbra and Ventura Counties

2.2.1. The Thomas Fire

The Thomas Fire began on December 4th, 2017, and was the product of two separate points of ignition. The first start was reported at 6:26 p.m. PST to the North of the city of Santa Paula, CA, near Thomas Aquinas College, after which the fire was named (VCFD.org). The second fire started approximately 30 minutes later to the Northwest of Thomas Aquinas College, between Ventura, Ca and Ojai, Ca near Koenigstein road and highway 150. Fueled by strong Santa Ana winds, the two fires quickly merged a few hours later and would consume nearly 100,000 acres within the first 48 hours (Nauslar et al., 2018).

Figure 4 Smoke plumes blowing offshore from Thomas, Creek, and Rye Fires. December 5th, 2017. https://socalgis.org/2017/12/05/satellite-image-thomas-creek-rye-fires/

Fanned by high wind speeds, drought conditions, rugged topography, and explosive chaparral, the fire quickly spread across Ventura and Santa Barbara counties. While the majority of the structure loss occurred within the first 48 hours, the Thomas Fire grew more than 60,000 acres a day on two separate days, 4-5 December and 9-10 December (Nauslar et al., 2018). The Thomas Fire was fully contained on January 12, 2018, having consumed 281,893 acres and was responsible for 1,343 structures damaged or destroyed, many of those primary residences. The Thomas fire was directly responsible for two deaths and was indirectly responsible for 21 additional deaths during the subsequent flooding and mudslides in Montecito, CA, as a result of the fire-damaged landscape.

2.3. Santa Ana Winds and Fire

Fast-moving, wind-driven wildfires are common to the Southern California landscape (Jin et al., 2015). Santa Ana wind events have been the cause of some of California's largest and most destructive wildfires, including the 1961 Bel-Air fire, 1993 Laguna fire, and the 2003 Cedar and Old fires (Fovell & Gallagher, 2018). However, even within the context of Southern California fire regimes, the winds experienced during the Thomas Fire were extreme. Reports from remote automated weather stations (RAWS) across Ventura County, CA, on December 4th, 2017, reported maximum wind speeds at >30 m/s (gusts > 67 mph). A long-duration wind event, such as the one that led to the Thomas Fire, had not been documented for 70 years (Fovell & Gallagher, 2018). This same long duration Santa Ana wind event was responsible for several other massive wildfires throughout Southern California during the same period. The Creek and Rye fires in Northern Los Angeles County burned 15,000 and 6,000 acres, respectively. At the same time, the Lilac fire in Northern San Diego county burned 5,000 acres and destroyed 157 structures (Nauslar et al., 2018).

Santa Ana winds are hot, dry, foehn winds that come out of the east or northeasterly direction from the deserts east of the Sierra Nevada mountain range towards the coast of Southern California (Raphael, 2003). The phrase “foehn winds” is a generic, collective title used to describe warm, dry downslope winds. They occur worldwide and throughout California under various names, such as chinook, sundowners, and diablo winds (Brinkmann, 1971). From Butte county in Northern, CA to San Diego, CA, in the South, annual winds have consistently driven large, destructive fires (Keeley & Syphard, 2019). Foehn winds, such as Southern California’s Santa Ana winds can reach speeds upward of 80 mph and significantly reduce the effectiveness of firefighting efforts (Fovell & Gallagher, 2018). These winds tend to occur in the late fall through early spring and are critical meteorological and social phenomena due to their relationship with wildfires (Raphael, 2003).

Many of California’s largest and most destructive wildfires have occurred as a result of wind events, with downed power lines often being the cause. As such, power companies across California are under pressure to turn off the power grid during wind events. This has obvious social implications as many residents do not have generators, and public facilities are not equipped to spend extended periods without power (Keeley & Syphard, 2019).

2.4. The Wildland Urban Interface

The Wildland Urban Interface (WUI) is the area where human development and wildland vegetation meet or intermingle (Kocher & Butsic, 2017). Fires in the WUI threaten lives and communities and cost an exorbitant amount in suppression dollars (Bar-massada et al., 2013). The WUI proliferated in the United States from 1990 to 2010, both in the number of new houses built and landmass (Radeloff et al., 2018) (Figure 5). Ventura County, CA, home of the 2017 Thomas Fire, has added over 100,000 inhabitants since 2000. The rapid population growth in urban areas of California has pushed more and more people to the fringes of metropolitan zones, thus encroaching on wild and fire-prone landscapes (Keeley & Syphard, 2019).

This amalgamation of housing developments with the natural environment has generated substantial environmental conflicts. Habitat fragmentation, damage to ecosystems, the introduction of invasive species, biodiversity decline, and increased threat of wildfire are all consequences related to the expansion of the WUI (Radeloff et al., 2018). Despite the growing awareness of the impacts of wildland fire in the WUI, there lacks consensus amongst land managers and fire scientists as to what housing to vegetation ratio constitutes the WUI.

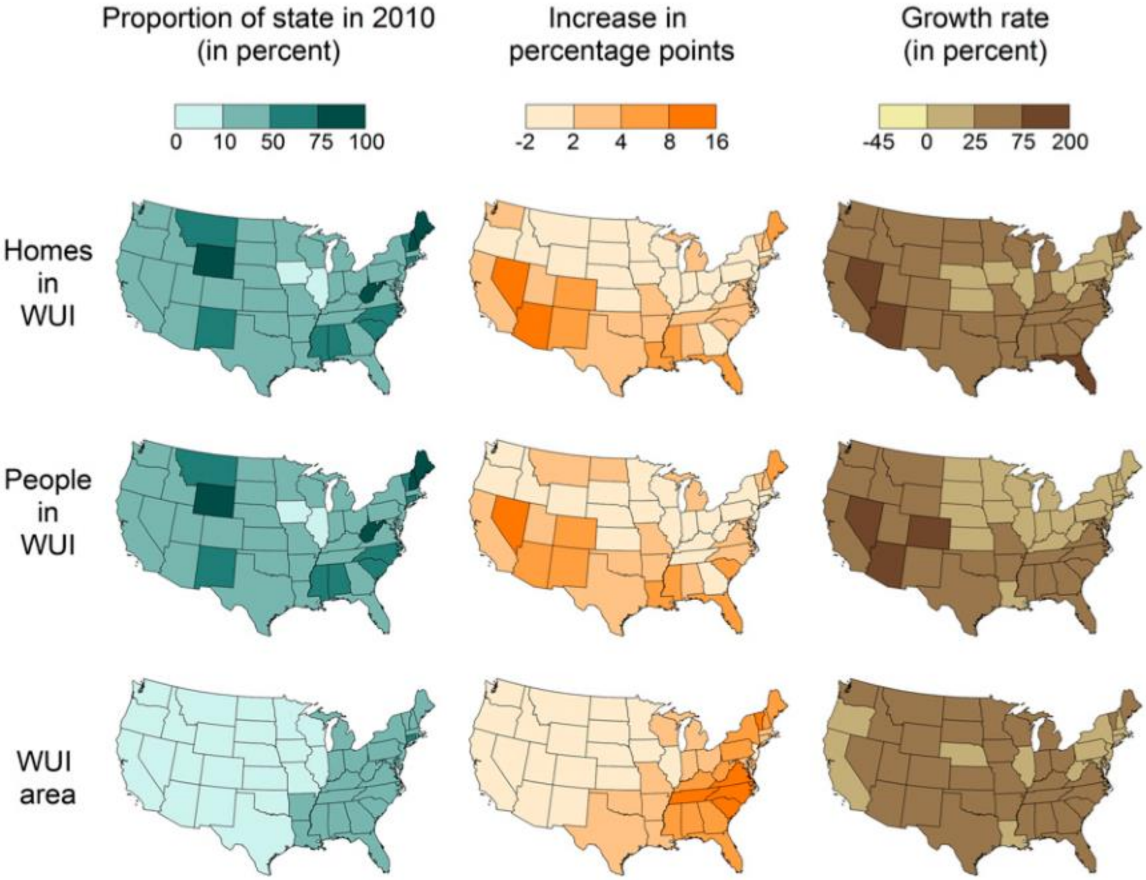


Figure 5 Change in WUI percentage from 1990-2010. WUI area calculated as the percentage of the state total in 2010.

(Excerpted from Stewart et al., 2007)

According to the 2001 federal registry, there are three types of WUI: Interface, intermix, and occluded (Federal Register : Urban Wildland Interface Communities Within the Vicinity of Federal Lands That Are at High Risk From Wildfire, 2016). While federal wildland fire policy is generally based on this definition, it does not account for varying risk within each community (Radeloff et al., 2005). Fire suppression and land management on federal lands rely upon the parameters set by the federal registry. Thus, it is vital to understand the differences between the three categories.

2.4.1. Intermix

Intermix WUI is an area where housing and vegetation intermingle (Radeloff et al., 2018). These areas tend to be in more rural settings where homes are scattered around the landscape with large areas of wild vegetation and open space amongst housing or developed zones (Stewart et al., 2007). Intermix WUI has interwoven continuity between structures and vegetation across the landscape leading to a lack of a defined border between wildland and urban development. The density of structures ranges from one structure to every 40 acres or a population density of 28-250 people per square mile (*Federal Register :: Urban Wildland Interface Communities Within the Vicinity of Federal Lands That Are at High Risk From Wildfire*, 2016). Wildfire is an inevitable, natural process in most areas of the United States for intermix communities (Bracmort, 2014). The mix of large amounts of wildland vegetation close to structures and an increased risk of human ignitions poses significant challenges to the development of mitigation strategies and for fire suppression activities (Shafran, 2016).

Many researchers have attempted to build on the definition provided by the Federal registry to more accurately define and map the WUI based on finer scale modeling. By utilizing varying combinations of population density, vegetation type, vegetation aggregation, and housing density, scientists have been able to map the WUI with varying degrees of accuracy and thoroughness. (Bar-massada et al., 2013). However, each method has inherent biases that lead to inaccuracies or inconsistencies across differing landscapes (Caggiano et al., 2016). Relying too heavily on building footprints can result in inaccurate housing density, while misclassifying vegetation can alter risk perceptions.

Fire policy in regards to the WUI is reflected in the terms in which the WUI is defined (Bar-massada et al., 2013). The lack of consensus amongst land management professionals leads to misallocation of resources and inaccurate community risk assessments. The WUI is where wildfires pose the most threat to life and property, require the largest amount of resources and cost the most (Radeloff et al., 2005). Therefore, it is paramount that research scientists, land management professionals, and fire managers continue to develop methods to define and map the WUI in order to reduce the impacts of catastrophic wildfire.

2.4.2. Interface

Interface WUI abuts or is near to wildland vegetation (Radeloff et al., 2018). Large tracts of urban development and suburban sprawl are typical examples of interface WUI. According to the federal registry, the development density is three or more structures per acre or population density greater the 250. These are areas with high levels of housing density adjacent to areas with at least 75% of vegetation cover (Stewart et al., 2007). While interface communities tend to have less vegetation intermixed amongst homes, the density of the homes themselves acts as a continuous fuel bed in the event of a wildfire. Fires in the interface WUI lead to higher recovery costs than a traditional wildland fire, as well as a higher number of people impacted than areas with lower housing density (Olsen et al., 2017). Recent fires in California, such as the 2017 Thomas Fire or the 2018 Woolsey Fire, have impacted developments miles away from wildland vegetation and the flaming front. Interface communities are at higher risk during wind dominated fires as firebrands, or embers, carried by strong winds can start community-wide conflagrations (Kramer et al., 2019).

2.4.3. Occluded

Occluded Communities generally exists within a city where structures abut an island of wildland fuels, such as a park or open space. There is a clear separation between structures and wildland fuels. The development density for an occluded community is generally similar to those found in the interface community; however, the occluded community surrounds or isolates wildland vegetation and tends to be less than 1,000 acres in size.

Each of these three communities poses specific risk factors and obstacles for suppression activities. Moreover, the categories defined by the federal registry attempts to define the WUI on a national scale but fail to recognize the risk to communities at a smaller spatial scale. Homes destroyed in the WUI are influenced by specific local factors and need to be analyzed based on a finer scale model (Bar-massada et al., 2013). Thus, it is critical that researchers continue to develop new strategies to define and analyze the WUI.

2.5. Defensible Space as Fire Defense

The rise in fire activity over the last decade has seen the number of people directly affected by wildfire increase dramatically (Syphard et al., 2017). Climate change, coupled with population growth and the continued development within the wildland urban interface (WUI), has left California communities at an increased risk of falling victim to the devastating effects of wildfire. This surge in fire activity has led to the creation of strict defensible space laws and building codes designed to reduce the risk of wildfire (Olsen et al., 2017). However, despite new regulations, structure loss as a result of wildfire is increasing at an alarming rate (Syphard et al., 2017).

To date, wildfire mitigation has focused on vegetation management in the wildlands, but little effort has been placed on homeowner responsibility (Radeloff et al., 2018). However, given that 99% of wildfires are anthropogenic and the inevitability of wind-driven wildfires across the California landscape, there is a need to move beyond strictly relying on defensible space to stop wildfires.

A defensible space of 100 feet around structures has been associated with structural survivability (Syphard et al., 2014). Adequate defensible space also increases the safety of fire personnel conducting suppression activities. However, defensible space has been shown to provide little protection for homes during large scale wind events. Instead, urban ignitions have been tied to fire branding and ember cast driven by fast-moving wind leading to urban conflagration (Keeley & Syphard, 2019). Images from catastrophic wildfires in recent years have shown communities decimated by wildfire while the surrounding live, irrigated trees are left untouched, leaving scientists to theorize that adequately watered vegetation around homes may provide an ember catch during wind events (Keeley & Syphard, 2019).

Rapid growth in areas prone to wildland fire has raised the wildfire risk nationwide (Radeloff et al., 2018). According to the US Census, in 2000, one out of eight people in the US live in California. As previously stated, the location and timing of Santa Ana wind events of Southern California are relatively predictable (Nauslar et al., 2018). Consequently, homes built in the Wildland Urban Interface (WUI) in areas prone to Santa Ana winds are essentially treated as dead fuels when the inevitable wind-driven wildfire encroaches on these neighborhoods (Keeley & Syphard, 2019). Thus, further research is needed to assess the effectiveness of mitigation factors specific to the WUI during wind events.

Since the beginning of the 21st century, California has experienced a dramatic increase in deadly and destructive wildfires (Keeley & Syphard, 2019). California's insatiable development practices have increased the number of people who live, work, and recreate in the WUI (Garnache, 2018). The expansion of the WUI in California has allowed a relatively limited number of anthropogenic ignitions to destroy entire communities (Nauslar et al., 2018). While scientists agree that the WUI is expanding, sprawling suburban development has made it difficult to define the line between the WUI and urban areas.

2.6. Building Materials for Structure Protections

The recent increase in wildfire frequency and the extent of structure loss as a result of wildfire has led to increased research into understanding community vulnerability to fire and what factors influence structure loss (Syphard et al., 2017). The number of structures within designated WUI areas rose dramatically between 2000 and 2010 (Radeloff et al., 2018), as such, structure loss within the WUI has significantly increased over the last few decades (Hakes et al., 2017). These facts highlight the need for community planners to consider the broad suite of factors involved when considering wildfire mitigation strategies (Syphard et al., 2017).

Historically, community wildfire mitigation programs have focused on fuels based hazard assessments and fuels management (Syphard et al., 2017). These strategies have given rise to mitigation programs, such as defensible space, which target vegetation that surrounds structures. However, defensible space has proven to be less effective during wind-driven fires where lofting embers can ignite homes far from the flaming front (Keeley & Syphard, 2019). The Kilcrease Circle community (Figure 6), which was

destroyed during the 2018 Camp Fire in Paradise, CA, is an example of a wind-driven fire in which lofting embers were responsible for structure loss rather than a buildup of biomass next to structures (Keeley & Syphard, 2019).

Figure 6 Kilcrease Circle Neighborhood destroyed in the 2018 Camp Fire, Paradise, CA

Recent studies have shown that structure loss due to wildfire depends on the design and materials used in the construction of the building (Syphard et al., 2014). As structures in the WUI are exposed to radiant heat, flame impingement, or firebrands during a wildfire, the actual components of the structure may determine whether it will begin flaming directly, smolder or resist ignition (Hakes et al., 2017). As such, many areas are enacting specific building regulations for all homes built within the WUI (Syphard et al., 2017). In California, for example, Chapter 7a of the California Building Code regulations apply specifically to new homes constructed in the WUI.

Studies have shown that the essential factors in determining structure loss within the WUI during a wildfire are exterior siding, roof type, windowpane type, and window frame material (Syphard et al., 2017). These factors can reduce the possibility of embers entering the home during a fire, which is more critical to home survival than defensible space during wind-driven events. Reducing the possibility of ember intrusion through structural fortification can increase survivability during a wildfire (Dicus, Leyshon, & Sapsis, 2014). Images from catastrophic wildfires in California over recent years have provided evidence that fire behavior in urban communities during high wind events has been driven by buildings rather than wildland fuels (Keeley & Syphard, 2019).

The Office of The State Fire Marshall of California is responsible for maintaining and amending the California Building Code (CBC) Chapter 7a. CBC Ch. 7a requires that all new homes built after January 1, 2008, which fall within State Responsibility Areas (SRA) and are within designated Fire hazard severity zones, follow specific building material guidelines proven to reduce the structural vulnerability. CBC Ch. 7a also applies to older homes being remodeled when a permit was issued. However, requirements for secondary or ancillary structures are vague and challenging to enforce.

Given these factors, homeowner education is paramount to the success of community-wide wildfire mitigation strategies. Homeowners must understand the relative effectiveness and importance of building materials during new construction and remodels to make sound decisions about what steps to take for successful wildfire mitigation. Preventing structure loss due to wildfire is not reliant on one single factor; instead, it is the combination of a myriad of factors that may differ from one community to the next. Thus, a holistic approach to reducing wildfire risk, including defensible space, building materials, and land use planning, is essential to preventing future loss in the WUI (Paveglio et al., 2015).

CHAPTER 3. **FIRE POLICY IN THE US**

3.1. Introduction

The Wildland Urban Interface (WUI) is the area where urban development meets or intermingles with wildland vegetation (Rahman & Rahman, 2019). While the concept of fires in the WUI is not a new phenomenon, structure loss to wildfire has increased dramatically in recent years (Hakes et al., 2017). Traditional mitigation strategies have mainly focused on fuel reduction programs to reduce direct flame contact with structures. Despite aggressive vegetation management programs and continued mitigation efforts, home loss under extreme wildfire conditions continues to be a national issue (Syphard et al., 2012). Recent studies have shown that housing arrangement and building characteristics play a vital role in structural survivability during a wildfire. As such, the WUI problem is beginning to be recognized as a structure ignition problem (Hakes et al., 2017) rather than strictly a result of geographical location or proximity to wildland vegetation. Structures themselves contribute to fire behavior, exclusive of the wildland vegetation that surrounds them and should be included as fuel in fire behavior modeling simulations rather than as passive components of a dynamic system.

The variety of wildfire codes and regulations that apply to the WUI are plentiful, with a considerable amount of overlap and redundancy. The breadth of codes and local provisions applicable to homes in the WUI can be confusing to land managers and residents alike (Brzuszek & Walker, 2008). Large multinational organizations such as the International Code Council (ICC) and the National Fire Protection Association (NFPA) work to promote international awareness of wildfire issues, codes, and standards on a global scale. Within the US, individual states have the authority to create and adopt regulations to protect the health, safety, and welfare of their citizens on a local scale (Holmes et al., 2008). In this capacity, numerous county and local governments have established regulatory programs to reduce wildfire hazards in high-risk areas. However, the deluge of new ordinances and policy changes after catastrophic incidents have done little to reduce the number of homes lost every year. (Leyshon et al., 2014).

Few states have adopted individual, statewide WUI regulatory codes. The majority of the US states choose to follow the National Cohesive Wildland Fire Management Strategy, National Fire Protection Association (NFPA), and International Code Council (ICC) codes and standards (Brzuszek & Walker, 2008). However, these programs guide the development of policies, and the interpretation of such policies is debatable. The lack of an agreed-upon definition of what constitutes the WUI coupled with non-standardized mapping programs has resulted in ineffective mitigation programs (Platt, 2010). The lack of consistency amongst federal agencies has caused some western states such as Oregon, Washington, and California to develop their own WUI mitigation strategies.

Despite efforts to standardize WUI regulations, inconsistency remains a constant. Even amongst Western states, other than California, where massive, destructive wildfires are frequent, there is little consensus on what constitutes best practices. In Washington, the extent of defensible space required can range from 30’-100’ and is slope and fuel dependent. In Oregon, defensible space requirements are determined based on fuel and roof type in up to seven zones around the home. Nearly all western states interpret defensible space differently with varying degrees of enforcement. Often the extent of mitigation efforts required relies on the homeowner to decide and self-report upon completion, which leaves regulations up to further interpretation and error.

Compared to all other states, California, by far, has the highest number of ordinances relating to landscape features and building materials for homes in the WUI and the strictest guidelines regarding vegetation (Brzuszek & Walker, 2008). These policies are a direct result of numerous catastrophic wildfires that have occurred in California in recent history (Table 1). The 1980s, and into the early nineties, were pivotal in California regarding policy responses to catastrophic wildfire (Brzuszek & Walker, 2008). California enacted the first statewide regulation in 1982 after massive wildfires burned across San Bernardino, Napa and Los Angeles counties with the requirement that land will be classified into fire hazard severity zones (FHSZ) (Koss et al., 1996).

Table 1 WUI Codes and Standards in use in California

Policy	**Organization**	**Description**
NFPA 1141	National Fire Protection Association	Standard for fire protection infrastructure for land development in wildland, rural and suburban areas.
NFPA 1142	National Fire Protection Association	Standard on water supplies for suburban and rural firefighting
NFPA 1144	National Fire Protection Association	Standard for reducing structure ignition hazards from wildland fire
International Wildland Urban Interface Code (IWUIC)	International Code Council	IWUIC covers many of the same concepts as NFPA (Brzuszek & Walker, 2008). It addresses regulations for land use and the built environment in the WUI. All regulations are supported by data collected from wildfire incidents, technical reports, and mitigation strategies form around the world.
CA Public Resources Code (PRC) 4201-4204	CA State Legislature	Provides requirements for the classification of land within the SRA per the severity of the hazards present in order to identify mitigation strategies to reduce the impacts of wildfire
CA Public Resources Code (PRC) 4290	CA State Legislature	Provides standards for infrastructure related to fire equipment access, safety, and minimum private water supplies for structures in the SRA and within an FHSZ. Maintains standards for fuel breaks and green belts to reduce fire activity.
CA Public Resources Code (PRC) 4291	CA State Legislature	Requires vegetative defensible space around structures of 100 feet, or to the property line, from each side of the building, including front and back. The first 30 feet of clearance shall be more intense as this area is critical for home defense against wildfire. Insurance companies and local jurisdictions may impose additional requirements.
CA Building Code Ch. 7a	CA Buildings Standard Commission	Establishes minimum building standards for the protection of life and property for any home within the SRA and in any FHSZ. Building standards are intended to resist the intrusion of embers and flame contact by promoting vegetative defensible space and building materials that are noncombustible, have a fire-resistance rating and block entry points for embers.

Policy	**Organization**	**Description**
CA Fire Code Ch. 49	CA Buildings Standard Commission	Provides minimum standards for the ability of a structure to resist intrusion by embers or flames from wildfire. Guidelines within the CA fire code are taken directly from IWUIC, NFPA, CBC CH. 7a and CA Public Resource Codes standards
CA Health and Safety Code Part 5 Abatement of Hazardous weeds and rubbish	CA State Legislature	Requirements for the abatement and management of vegetation growing on streets, sidewalks and private property in any county in CA, to include any fire protection district for wildfire mitigation
CA Health and Safety Code Part 6 Abatement of Hazardous Weeds and Rubbish: Alternative Procedure	CA State Legislature	Allows the board of supervisors to compel private property owners to remove hazardous materials from such properties. If the property owner fails to comply, the board of supervisors may authorize the removal of such material at the owner’s expense.

The first state-wide law specifically targeting vegetation (defensible space) came in 1985 with Public Resources Code 4291 (PRC 4291). PRC 4291 initially required homeowners to maintain a 30’ buffer, since increased to 100’, of defensible space, not to exceed the property line, around structures. Defensible Space is an area around a building in which vegetation, debris, and other types of combustible fuels have been treated, cleared, or reduced to slow the spread of fire to and from the building (Defensible Space, 2008). The 1989 49er fire in Nevada County, California, which burned 312 structures, was the catalyst for the California legislature to enact fire-safe regulations in the form of Public Resources Code 4290, which further developed regulations for roads and access. The 1991 Oakland Hills firestorm continued to push new legislation towards wildfire safety and preparedness in residential communities with the Bates Bill. The Bates Bill requires Cal Fire to work with local governments to identify fire hazard severity zones in areas considered Local Responsibility Areas (LRA) (Dicus et al., 2014).

These actions have put California at the forefront of wildfire mitigation policy. Repeat incidents of catastrophic wildfires in California have implored regulators to develop an abundance of new policies or expand on existing policies in an effort to combat the impacts of wildfire. These efforts, however, have had little success at reducing home loss in a state with an ever-increasing population. California leads the US in catastrophic wildfire occurrence with over 1.8 million acres burned (“National Interagency Fire Center,” n.d.), nearly 100 people killed, and over 20,000 structures lost during the 2018 fire season alone (“Facts + Statistics: Wildfires | III,” 2019). Catastrophic wildfires, however, are an annual disturbance amongst all Western states. Most states have some form of regulations regarding wildfire hazards.

This study aims to summarize pertinent WUI codes and regulations in the western US. California, as a leader in wildfire mitigation, will be the focus of this study, to include the six contract counties (Santa Barbara, Kern, Orange, Los Angeles, Marin, and Ventura). However, relevant regulations from neighboring western states will be provided as reference.

Contract counties are provided funding by the State to provide fire protection and prevention services to state responsibility area (SRA) lands within their boundaries (Informational Report for State Responsibility Area Prevention, 2017). State responsibility areas are lands where the State of California is financially responsible for the prevention and suppression of wildfires. All land in California falls into one of three categories regarding financial responsibility for fire suppression and prevention (Fig. 7). Local responsibility areas (LRA) apply to local municipalities and lands that fall within city or town limits. Federal responsibility areas are lands managed by federal agencies such as the US Forest Service (USFS), Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), etc. (Fig. 7).

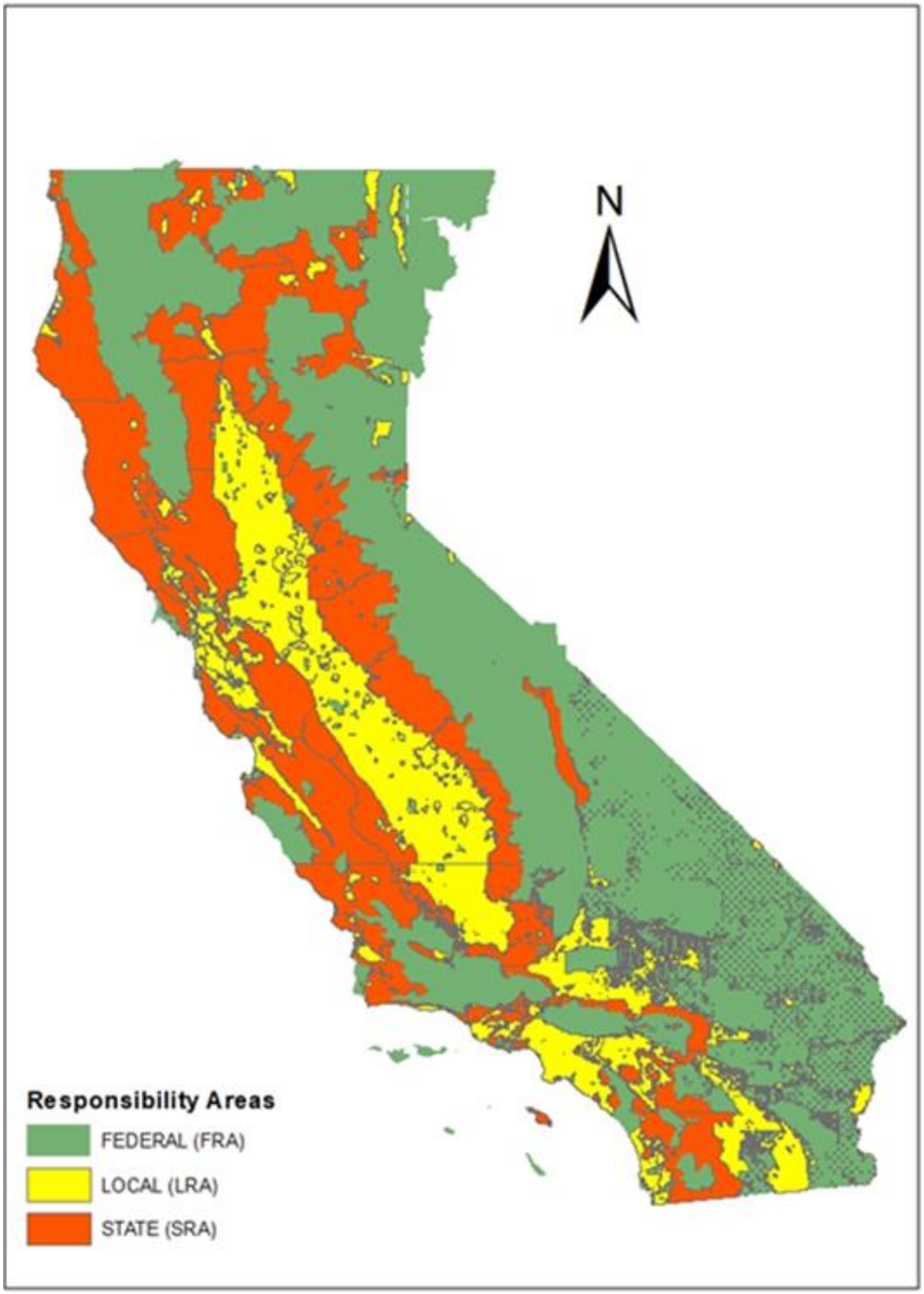


Figure 7 Map of CA divided into State, Federal and Local responsibility areas.

The primary focus of this study is the current WUI codes and standards in use in California. WUI codes and standards in other western states are included as a reference and for comparison purposes. Additionally, this summary will focus on these policies, which represent practical solutions for individual homeowners to reduce the risk of structure loss in the event of wildfire within the context of the WUI.

3.2. Methods

California is a leader in wildfire mitigation practices, policies, and regulations in the WUI. Owing to the propensity of destructive wildfire, population growth, and increasing development into the WUI, California has more comprehensive and strict wildland fire protection standards of any state (Brzuszek & Walker, 2008).

We collected data on national and statewide WUI mitigation programs in use throughout western US states from multiple jurisdictions. We compared and analyzed standard best practices in use regarding building materials and defensible space. Many of them overlap or have subtle differences based on jurisdiction. Further, some counties have created stricter codes for areas which lie in Very High Fire Hazard Severity Zones (VHFHSZ). Fire hazard severity zones are established and defined by the California Department of Fire and Forestry and are described in detail in the following section. Additionally, we developed a matrix describing specifics for common mitigation practices and where the apply (Table 2).

3.3. Fire Hazard Severity Zones (FHSZ)

3.3.1. CA Public Resource Codes (PRC) 4201-4204

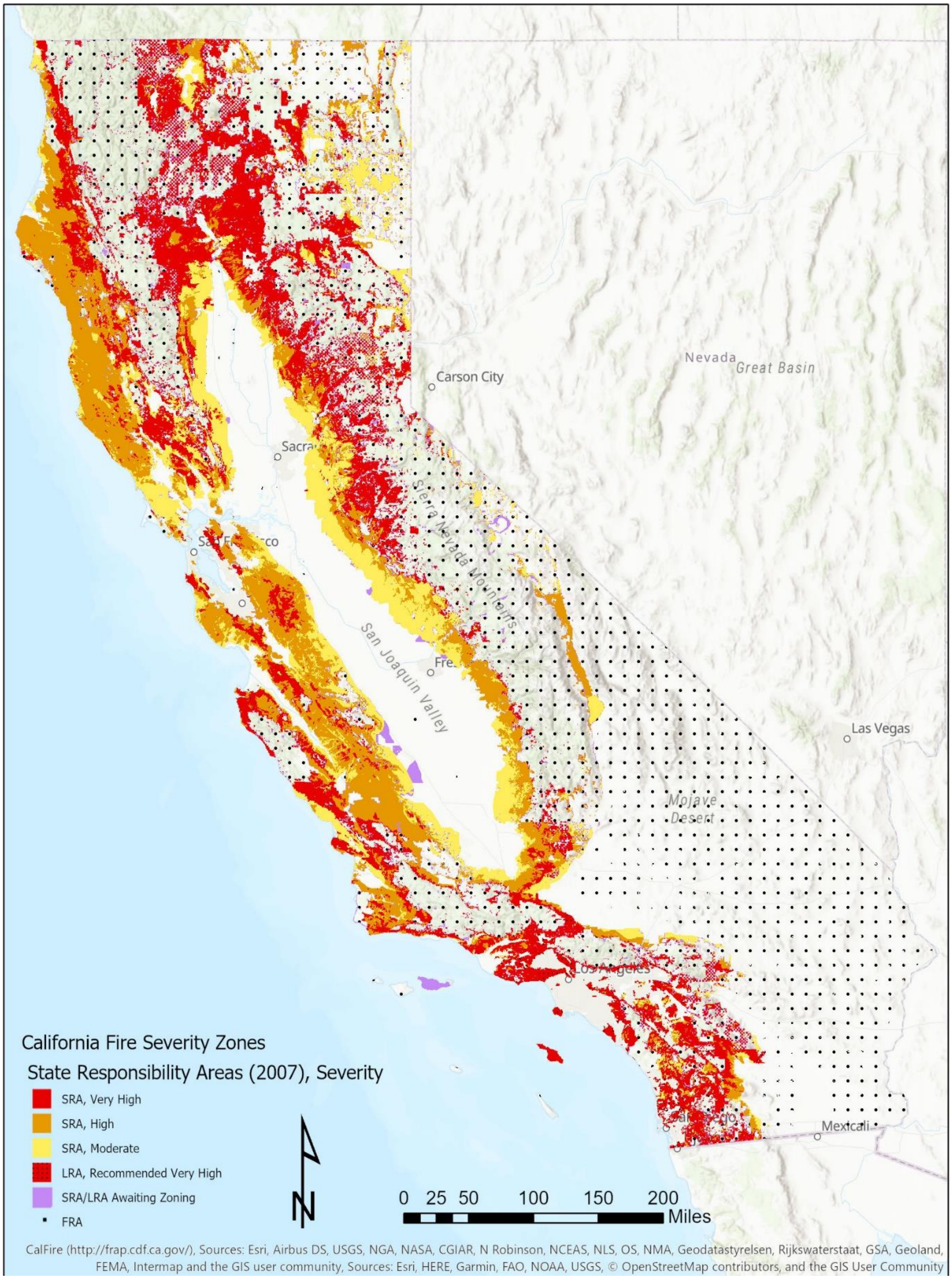
Senate Bill 81, passed in 1982, requires the California Department of Forestry and Fire Protection (Cal Fire) to establish Fire Hazard Severity Zones (FHSZs) within State Responsibility Areas (Fig. 8). FHSZs are rated as moderate, high, or very high severity zones based on fuels, topography, weather, and other relevant factors influencing fire behavior. The goal of FHSZs is to provide specific designations for the application of mitigation activities, which include defensible space, and the use of specific building materials within the WUI. Initially, however, FHSZ designation only included homes under Direct Protection Authority (DPA) of the State fire protection agency and therefore did not have the authority to enforce policies on federal responsibility area (FRA) or on local responsibility areas (LRA).

As a result of the 1991 Oakland Hills fire, which burned mostly within the LRA, the 1992 Bates Bill required Cal Fire to work with local jurisdictions to establish High (HFHSZ) and Very High Fire Hazard Severity Zones (VHFHSZ). LRA typically consists of land that falls within incorporated cities, cultivated agricultural lands, and non-flammable areas in unincorporated areas.

Local governments may choose not to accept designations due to fear of losing home insurance, increased home insurance costs, lower property values, and increased construction costs (Leyshon et al., 2014). Further, LRA lands are only included if the parcel is designated as a VHFHSZ and if the local jurisdiction has elected to accept the state’s recommended designation. This lack of consistency across jurisdictions leaves a patchwork of communities throughout California where mitigation efforts have been achieved while others have not. This dichotomy presents issues to fire managers when attempting to achieve landscape-level mitigation strategies.

Moreover, FHSZ designations identify the potential fire hazard (not risk) in a given area in the absence of mitigation activities. “Hazard” is defined here as the physical condition that can lead to damage to a particular asset or resource. Thus, fire hazard involves the physical conditions related to fire and its ability to cause damage (Leyshon et al., 2014). Therefore, fire hazard only refers to the potential fire behavior and fire activity of the fire itself under certain circumstances. Risk, however, is defined as the likelihood of loss by wildfire (Leyshon et al., 2014). Thus, a home designated as being in a VHFHSZ might be at low risk of loss due to proper construction materials and maintenance of vegetative fuels. Similarly, a home might be in a moderate FHSZ (the lowest designation) but be at high risk of burning if the home is constructed with combustible materials and has dense, flammable vegetation that abuts the structure.

Given the confusing nature of FHSZ designation, it may be difficult for homeowners to decipher their actual risk and, therefore, have difficulties choosing effective mitigation strategies. Furthermore, FHSZs are rarely updated, and severity status does not change regardless of mitigation efforts. Thus, it is difficult for homeowners to know if their efforts have made any difference. Once a home is identified as belonging in an HFHSZ, it will remain in an HFHSZ despite mitigation effort



CalFire (http://frap.cdf.ca.gov/), Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 8 CA Fire Hazard Severity Zones

3.4. Vegetative defensible space and fuel modifications for structure protection

A study by Syphard et al. (2017) demonstrated that defensible space is indeed a factor in structural survivability during a wildfire. However, the extent of defensible space necessary varies based on local factors and is not effective beyond 58’ from the structure (Syphard et al., 2017). There have been numerous studies that suggest that a reduction in flammable vegetation from the immediate vicinity of structures will reduce the risk of ignition from radiant heat and direct flame contact; however, enforcement is variable (Hakes et al., 2017). Firewise guidelines, National Fire Protection Association (NFPA) and the International Code Council (ICC) WUI code recommend the maintenance of the Home Ignition Zone (HIZ) to prevent the transmission of small flames via vegetation or debris piles on to adjacent homes. Firewise USA defines the HIZ as “an area that includes your home and its immediate surroundings.” The HIZ, as defined by the IWUIC and NFPA, is divided into three zones from the structure (0-5’ immediate zone, 5’-30’ intermediate zone, and 30’100’ extended zone). CA PRC 4291 divides defensible space into two zones while some contract counties extend defensible space to 200’ for homes in a VHFHSZ. Theoretically, the reduction in fuel and debris from the structure prevents direct flame impingement and a safe area for suppression resources. Given this focus on vegetation management for structure protection, the traditional strategy of fuel reduction around homes continues to receive most of the attention (Syphard et al., 2014) and shape community-wide mitigation efforts.

California has several state regulations addressing defensible space around homes within the SRA; PRC 4290, PRC 4291, and Title 14 of the Natural Resources Code. PRC 4290 addresses firefighter access, infrastructure, and fuel breaks around communities designated as being within an FHSZ. Title 14 of the Natural Resources Code (CCR 1299) and PRC 4291 deal more directly with vegetation immediately adjacent to the home and separates defensible space into two zones. The first zone (Zone 1) extends from the structure out to 30’ or the property line and has more restrictive vegetation requirements than zone two. Zone 2 extends 30’ to 100’ from the structure or property line, whichever comes first (Fig. 9).

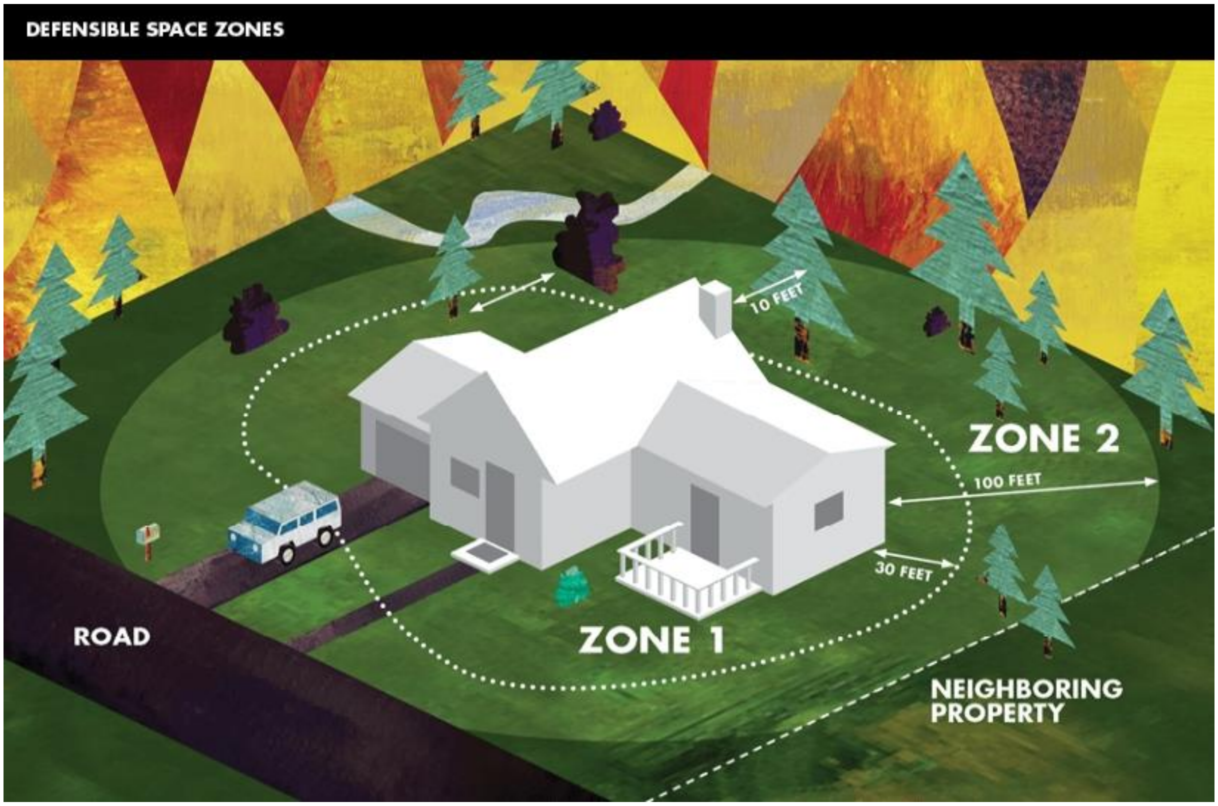


Figure 9 PRC 4291 Defensible Space Zones. (CalFire.ca.gov)

PRC 4291 states, “Fuels shall be maintained in a condition so that a wildfire burning under average weather conditions would be unlikely to ignite the structure”

(California Legislative Information, n.d.). However, scientific research is weak on the actual effectiveness of vegetation modification to reduce structure loss, and most recommendations regarding defensible space are based on expert opinion (Syphard et al., 2014). California landscapes are subject to extreme winds, and vegetation is often not a factor in fire spread, rather urban conflagrations driven by high winds and ember cast are to blame for structure loss (Keeley & Syphard, 2019). The 2017 Tubbs Fire in Santa Rosa, CA, the 2017 Thomas Fire in Ventura, CA, and the 2018 Camp Fire in Paradise, CA, are all examples of fast, wind-driven fires that burned under extreme conditions and collectively resulted in 25,510 buildings destroyed (Keeley & Syphard, 2019).

Some counties in California have taken a stricter approach to defensible space. Marin and Los Angeles county, for example, require defensible space up to 200' feet from the structure and 10' clearances around driveways and access routes. Additionally, developments and local municipalities across California have established their own guidelines that reflect local topographic and weather conditions. A California Senate Bill (SB 1618) was introduced in 2008 to relax environmental restrictions and to encourage increasing defensible space requirements to 300 feet (Syphard et al., 2014). However, these regulations are the result of the assumption that fuel is the primary driver of wildfire despite a lack of empirical data (Syphard et al., 2012).

Throughout the West, defensible space policy varies considerably. Some jurisdictions require up to 300,' and non-compliance is punishable with fines, while in other areas, only 30' is recommended and self-reported. Table 2 lists defensible space guidelines appliable throughout California and across other western states. National and statewide guidelines are included for reference as well as local policies specific to Santa

Barbara and Ventura cities, both of which were impacted by the 2017 Thomas fire. Without mandated federal regulations, states are left to develop their own defensible space requirements. This has created a patchwork of confusing defensible space regulations throughout the West.

Furthermore, defensible space policy takes a uniform approach, or blanket policy, towards the reduction of the impacts of wildfire (Kramer et al., 2019). The fire environment is dynamic; different landscapes present multiple variables to the wildfire problem. As such, mitigation strategies should be developed to reflect the unique challenges present in each community. For example, defensible space may be more practical in intermix WUI where homes are spread out and have significant amounts of vegetation between them. Whereas vegetation in high density, interface WUI communities is less of a factor during wildfires, and structure loss may be a result of spatial arrangement or building materials (Kramer et al., 2019).

Table 2 Defensible Space Policies and Guidelines Across Western States.

Agency/Jurisdiction	**Defensible Space**	**Building Components**
Cal Fire (PRC 4291)	2 zones • 0-30’ • 30’-100’	CBC Ch. 7a
Federal Agencies (USFS, DOI, NPS, BIA, BLM, FWS)	3 zones • 0-30’ • 30-100’ • >100’	IWUIC
Orange County (Contract) (VHFHSZ)	4 zones • 0’-2’ • 2’-30’ • 30’-100’ • >100’	CBC Ch. 7a
Los Angeles County (Contract) (VHFHSZ)	3 zones • 0’-30’ • 30’-100’ • 100’-200’	CBC Ch. 7a
Santa Barbara County (Contract) (VHFHSZ)	3 zones • 0’-5’ • 5’-30’ • 30’-100’	CBC Ch. 7a

Agency/Jurisdiction	**Defensible Space**	**Building Components**
Marin County (Contract) (All SRA)	5 zones • 0’-5’ • 5’-30’ • 30’-100’ • >100’ 0’-10’ (Access zone)	CBC Ch. 7a
Kern County (Contract) (All SRA)	2 zones • 0’-30’ • 30’-100’	CBC Ch. 7a
Ventura County (Contract) (VHFHSZ)	4 zones • 0’-5’ • 5’-30’ • 30’-100’ • 0’-10’ (access zone)	CBC Ch. 7a
City of Ventura	2 zones • 0’-30’ • 30’-100’	CBC Ch. 7a
City of Santa Barbara (VHFHSZ)	2 zones • 0’-30’ • 30’-100’	IWUIC

Agency/Jurisdiction	**Defensible Space**	**Building Components**
Colorado	3 zones • 0’-30’ • 30’-100’ • 100’+	NFPA/IWUIC
Washington	2 zones (slope and fuel-dependent) • 0’-30’ • 30’100’	IWUIC
Oregon	7 zones (fuel and roof dependent) • Distances based on risk analysis	IWUIC
Nevada	2 zones • 0’-30’ • 30’-100’	IWUIC
Montana	2 zones • 0’-30’ • 30’-100’	IWUIC
Arizona	3 zones • 0’-5’ • 5’-30’ • 30’-100’	IWUIC

Agency/Jurisdiction	**Defensible Space**	**Building Components**
New Mexico	2 zones • 0’-30’ • 30’-100’	IWUIC
Utah	3 zones • 0’-5’ • 5’-30’ • 30’-100’	IWUIC
Wyoming	3 zones • 0’-5’ • 5’-30’ • 30’-100’	IWUIC
Idaho	3 zones • 0’-5’ • 5’-30’ • 30’-100’	IWUIC
NFPA	3 zones • 0’-5’ • 5’-30’ • 30’-100’	NFPA 1144
ICC	Site Specific	IWUIC

3.5 Building Materials

Homes in the WUI burn either by direct flame contact, radiant heat from flames, or exposure to firebrands (Hakes et al., 2017). Once ignited, homes in high-density interface communities act as a continuous, dry fuel bed (Keeley & Syphard, 2019). Wildfires driven by extreme winds can quickly overcome entire communities and overwhelm suppression resources. The thermal energy produced by burning homes can significantly influence fire activity (National Institute of Standards and Technology, 2010). Therefore, understanding why and how structures ignite is paramount to reducing future structure loss during a catastrophic wildfire.

Three existing national and statewide building codes and standards guide most wildfire resistant construction. While many jurisdictions have established their own codes, they are based on standards established by:

- The International Code Council’s International Wildland Urban Interface Code (IWUIC)
- The National Fire Protection Association’s Standard for Reducing Structure Ignition Hazards from Wildland Fire (Standard 1144)
- The California Building Code Chapter 7A—Materials and Construction Methods for Exterior Wildfire Exposure

The IWUIC, NFPA 1144, and Chapter 7A generally distinguish between the performance of construction materials and their exposure to wildfire. While each standard offers protection against direct flame contact and ember exposure, there are discrepancies amongst them, which can lead to confusion by homeowners about best practices. The IWUIC and NFPA guidelines, for example, differ from CBC Ch. 7a regarding decking material. NFPA and IWUIC require that all decking material be constructed of ignition resistant material or one-hour fire rated heavy timber (Table 3). CBC Ch. 7a only requires that deck walking surfaces meet the same standards.

Home attachments such as decking and fencing materials are significant elements determining structural survivability during a wildfire. Jurisdictional boundaries are arbitrary in reference to wildfire mitigation. If embers manage to ignite the underside of a deck of a home following the less strict CBC Ch.7a guidelines, the probability of a neighboring home catching fire increases dramatically regardless of which set of guidelines they are following.

Multiple studies have shown that four main components are responsible for structural loss during a wildfire: Roofing material, window panes, exterior siding, and eave assembly (Bowditch et al., 2006). More research, however, is necessary to determine the structural ignitability via home attachments. Inconsistent guidelines and weak enforcement are only adding to the wildfire risk for communities living within the WUI. Table 3 offers a side by side comparison for NFPA, IWUIC, and CBC Ch. 7a guidelines and standards for construction materials in the WUI and is followed by explanations for each section.

Table 3 Comparison of WUI Codes and Standards.

Comparison of WUI Codes and Standards			
Component	**IWUIC (2018) Ignition-Resistant Class 1**	**NFPA 1144 (2018)**	**California Building Code Chapter 7A (2013)**
Roof			
Roof	Class A fire-rated roof covering required. Plug gaps at the end (bird stop) and underlayment full length of any valleys	Class A fire-rated covering required. Roof covering must be tested using all components in the as-built assembly. Where gaps exist between covering and roof deck, a rolling roof product shall be laid over the entire deck surface and gaps and end of ridge plugged with noncombustible material.	Requires a fire-rated covering, actual rating (Class A, B or C) dependent on fire hazard severity zone. Plug gaps at ends (bird-stop, fire stop) A minimum 36-inch-wide cap sheet must be installed under metal valley flashing.
Eaves & Fascia	Eaves and soffits protected by ignition-resistant material or one-hour fire resistant rated construction, or 1-ince fire-resistant treated lumber, or 3/4 -inch plywood. Fascia required, protected by ignition-resistant material or 1-hour fire-resistant-rated construction, or 2-inch dimensional lumber.	Eaves must be enclosed with fire-retardant treated wood, ignition-resistant materials, noncombustible materials, or materials exhibiting resistance to wildfire penetration. Metal drip-edge required on eave edges.	Soffited or open eave allowed. If open-eave, nominal 2x material required as backing.
Gutters	Noncombustible gutter (vinyl gutters not allowed). Use of gutter cover is required.	Use of noncombustible gutter and gutter cover device required.	Metal or vinyl gutters allowed. Installation of a gutter cover required.

Comparison of WUI Codes and Standards			
Component	**IWUIC (2018) Ignition-Resistant Class 1**	**NFPA 1144 (2018)**	**California Building Code Chapter 7A (2013)**
Vents	Vents covered by ¼-inch mesh screen. Vents in exterior walls shall not exceed 144 square inches or shall be designated/approved to prevent flame or ember penetration into the structure. Vents not allowed in under-eave areas. Gable end and dormer vents shall be >10 feet from lot line. Underfloor vent openings located as close to grade as practical.	Vents covered by 1/8-inch mesh screen or use of vents designed to resist flame intrusion and embers. Vents not allowed in under eave area.	General Requirement for vents to resist intrusion of embers and flame through ventilation openings. 1/16 to 1/8-inch mesh screening is specified. Vents not allowed in under-eave area unless vent has been accepted as ember and flame-resistant.
Exterior Walls			
Siding	Specifies compliance with one of five methods: 1) one-hour fire-resistant rated construction, 2) approved noncombustible materials, 3) heavy timber or log wall construction, 4) fire-retardant treated wood on exterior side, 5) ignition-resistant materials on treated side.	Specifies ignition-resistant material (including exterior fire-retardant treated wood) or an assembly with a minimum of one-hour fire rating. Six-inch noncombustible vertical separation required between a horizontal surface and siding.	Four options for compliance: 1) noncombustible material, 2) ignition-resistant material, 3) heavy timber construction, 4) log wall assembly, or 5) assembly complying with State Fire Marshal 12-7A-1 (10-minute direct flame exposure test).
Windows	At a minimum, all windows (including doors and skylights) shall be dual pane (multilayered) with tempered glass, or glass blocks or fire resistant rated of not less than 20 minutes.	Requires all windows (including in doors and skylights) to be tempered glass, multilayered glazed panels, glass block, or fire-resistance rating of not less than 20 minutes.	Four options for compliance: 1) multi-pane glazing with a minimum of one tempered pane, 2) glass block units, 3) fire-resistance rating of not less than 20 minutes, or 4) meeting performance requirements of SFM 12-7A-2

Comparison of WUI Codes and Standards			
Component	**IWUIC (2018) Ignition-Resistant Class 1**	**NFPA 1144 (2018)**	**California Building Code Chapter 7A (2013)**
Doors	Approved noncombustible construction, solid-core wood not less than 1 3/4 -inches thick, or fire protection rating of not less than 20 minutes.	Solid-core wood not less than 1 ¾ -inches thick, constructed of noncombustible material, or fire protection rating of not less than 20 minutes.	Four options for compliance: 1) Noncombustible exterior surface or cladding, 2) solid core wood meeting thickness specifications, 3) fire resistance rating of not less than 20 minutes, or 4) meeting the performance requirements of SFM Standard 12-7A-1.
Decks	One-hour fire-resistant-rated construction, heavy timber construction, or constructed with noncombustible materials or fire retarded treated wood or other ignition-resistant materials. A deck extending over a slope greater than 10% must be enclosed to within 6 inches of the ground using same exterior wall construction standards.	Requires heavy timber, noncombustible materials, fire-retardant treated wood, or other ignition-resistant material, or be a one-hour fire-resistance rated assembly.	Only applies to the walking surfaces of the deck. Four options for compliance: 1) ignition resistant material that complies with SFM Standard 12-7A-4, 2) exterior fire-retardant wood, 3) noncombustible material, or 4) comply with SFM Standard 12-7A-4.
Near-Home Landscaping			
Near-Home Landscaping	Does not explicitly address near-home landscaping but addresses fuel modification in 30+-foot defensible space area.	Does not explicitly address near-home landscaping but addresses location and maintenance of vegetation in two zones, including from the home to 30-feet, and from 30-feet to 100-feet, or to the property line.	Hazardous vegetation and fuel management required based on different fire hazard severity zones. Does not explicitly address near-home landscaping.
Note: Excerpted from Headwaters Economics (*Building a Wildfire-Resistant Home: Codes and Costs*, 2018)			

3.4.1. Roofing Material

Standards for roofing material follow the same testing protocols and are designed to withstand three fire-related characteristics: the spread of fire into the attic, resist flame spread on the roof, and the ability to resist the generation of firebrands. Roofing materials are ranked into three classes; Class A, Class B, and Class C. Class A roofs such as concrete or clay roof tiles, fiberglass asphalt composition shingles, or metal offer the most protection against wildfire. California homes built after 2008, within all FHSZs in the SRA, must have a Class A roof to comply with CBC CH. 7a. California building codes for fire resiliency also applies to upgraded roofs for homes within the SRA built before 2008. However, homes within the LRA are only required to have class A roofs if they are in a Very High Fire Hazard Severity Zone (VHFHSZ).

Although building codes follow standard testing methods, it has been argued that testing methods cannot mimic the dynamic properties of an actual wildfire (Hakes et al., 2017). Standardized tests do not address vulnerabilities that can occur at the edges where gaps can allow ember intrusion (Building a Wildfire-Resistant Home: Codes and Costs, 2018). Furthermore, roofs are an especially vulnerable structural component as there are numerous places where other components, such as vents and skylights, create points of entry for embers. Roofs are susceptible to debris accumulation in the form of leaves and pine needles and require constant maintenance. PRC 4291 attempts to deal with the issue of debris accumulation on roofs by requiring that homeowners clean off roofs and gutters; however, compliance is rarely enforced.

3.4.2. Window Systems

A study by Syphard et al. (2017) reports that homeowners in older developments should prioritize upgrading their windows to reduce wildfire risk. Windows provide a significant entry point for embers. Radiant heat from burning vegetation or structural materials has shown to break windows, which in turn allows ember intrusion into the structure (Hakes et al., 2017). Additionally, single-pane windows should be upgraded to double pane to reduce the thermal exposure of a wildfire to items inside the house and near windows. Double pane and triple-pane windows are also less likely to crack or break due to heat exposure or flying debris (Syphard et al., 2017).

Large scale studies by the National Institute of Standards and Technology (NIST) revealed that dual pane, tempered glass is unlikely to fail due to radiant heat from a wildfire (Hakes et al., 2017). Heat fluxes by direct flame contact can range from 20 kW/m^2 – 70 kW/m^2 depending upon what is burning. Typical heat fluxes during a wildfire often only reach 35 kW/m^2. A NIST study found that dual pane windows exposed to radiant heat at 35 kW/m^2 for 25 minutes did not fail (Hakes et al., 2017). These findings support recommendations for codes and standards for construction in the WUI.

3.4.3. Exterior siding and Eave Assembly

WUI building codes allow for the use of combustible and noncombustible materials for exterior wall and eave construction that meet fire-resistant guidelines (Building a Wildfire-Resistant Home: Codes and Costs, 2018). However, the use of ignition resistant material is always preferred, and combustible materials that meet fire-resistant guidelines should be used conservatively. Testing for exterior walls does not address flame spread vertically, or flame spread characteristics to other components. Large surface areas make exterior siding extremely vulnerable to radiant heat and direct flame impingement. (Hakes et al., 2017). As such, keeping debris and flammable material away from homes is as crucial as the siding itself (Hakes et al., 2017).

3.4.4. Home Attachments (Decks, Porches, Fences)

The treatment of home attachments in building codes is complex, and there has been little research on structural vulnerability due to building components such as fences and decks. IWUIC and NFPA codes limit decking construction to ignition resistant materials. Whereas CBC CH. 7a restricts decking materials based on the heat release rate of certain materials. Solid wood and plastic decking materials comply with CBC CH.7a but not with NFPA 1144 nor IWUIC (Building a Wildfire-Resistant Home: Codes and Costs, 2018). Both NFPA and IWUIC require ignition resistant decking materials, which are rated as noncombustible or ignition resistant such as steel framing and aluminum decking or pressure treated exterior fire-retardant-treated lumber.

Further discrepancies among codes and standards regarding decking components exist in their structural support systems. CBC CH. 7a only requires that the walking surfaces of decks comply with standards, and therefore, structural support beams do not need to comply with fire-resistant standards, whereas IWUIC and NFPA standards require structural support systems to be constructed of materials that have a fire-resistance rating. Neither code specifically addresses fence construction.

3.5. Discussion

California wildfires have destroyed tens of thousands of homes, cost hundreds of human lives, and displaced hundreds of thousands of people (Syphard, 2019). Globally, wildfires have caused escalating economic, social, and environmental damage (Kramer et al., 2019). At the time of this writing, Australian bushfires are wreaking havoc across the Australasia, scorching millions of acres and displacing thousands. The frequency of these types of events in recent years and the likelihood that these types of events will continue has created a sense of urgency to discover the underlying factors contributing to structure loss (Syphard, 2019).

There is a myriad of wildland fire policies affecting communities of all sizes (Brzuszek & Walker, 2008). Widespread adoption of WUI codes and standards outside of the SRA is inconsistent (Building a Wildfire-Resistant Home: Codes and Costs, 2018). Traditional methods of vegetation (fuels) management in the form of defensible space has been the primary focus of mitigation policy for decades and continues to receive the most attention (Syphard et al., 2014). However, there is little empirical evidence demonstrating the effectiveness of defensible space up to 100 ft., the typical distance required for compliance (Syphard, 2019).

Syphard et al. (2014) found that the most effective defensible space treatment was between 16-58 ft. from the structure with no additional benefit beyond that (Syphard et al., 2014). Moreover, defensible space has been shown to be most effective in WUI intermix communities rather than in WUI interface communities where wildfires cause the most significant amount of structure loss (Kramer et al., 2019). Despite this seeming dichotomy, Cal Fire deploys an army of defensible space inspectors throughout the state each fire season to enforce CA PRC 4291 on SRA land regardless of the type of development or housing arrangement. Individual contract counties and local homeowner associations have stricter guidelines than those required on SRA land. However, these stricter guidelines rely on “expert opinion” or outdated research (Syphard et al., 2014).

Except for SRA land in CA, widespread adoption of WUI codes and standards is sporadic (Building a Wildfire-Resistant Home: Codes and Costs, 2018). Within the context of LRA land, numerous legal loopholes provide leeway for communities to keep land from being designated as VHFHSZ. Many communities cite reductions in property value and rising insurance costs as reasons to stay away from the designation (Troy, 2007). The lack of consistency amongst neighboring communities, coupled with lax enforcement, creates undue burden and confusion for homeowners.

Building regulations and mitigation policies are ineffective if not enforced. Societal response to risk management at a local level, where the most significant control over mitigation occurs, is problematic (Winter et al., 2009). Compliance in the absence of enforcement is not practical. The seat belt compliance rate rose from 14 percent in 1984 to nearly 70 percent by 1998 as more states adopted seat belt legislation and strict enforcement (NHTSA, 1999). Without increased enforcement and programs designed to aid the financial burden of mitigation, homeowner compliance for the very policies designed to protect them will suffer.

Structure loss due to wildfire is complex and is the product of numerous variables (Keeley, Safford, Fotheringham, Franklin, & Moritz, 2009). Knowledge of structural ignition has advanced significantly over the last several decades (Hakes et al., 2017), yet;

structures are still burning at alarming rates. Meaningful gains can be made towards protecting communities through increased public awareness and education, enforcement, and standardized building standards and codes across jurisdictional boundaries. Simply creating more codes and policies will not protect communities from the devastating effects of wildfire.

CHAPTER 4. **FACTORS CONTRIBUTING TO STRUCTURE LOSS ON THE THOMAS FIRE**

4.1. Introduction

Even with ever-increasing budgets dedicated to fighting wildfires and strengthening of codes and regulations to make communities more fire-resilient, losses to the built and natural environment are on a steep, upward trend in both California and throughout many parts of the world. Indeed, 15 of the top 20 most destructive wildfires in California history occurred in the 5-year period between 2015-2020, causing 158 fatalities and destroying 42,418 buildings.

Increasing WUI fire losses are due to a myriad of factors, including burgeoning development in fire-prone areas (Dicus et al. 2014), fuel accumulation following a century of fire exclusion policies (Keane et al. 2002), structures built with materials that are not ignition-resistant (Cohen, 2000), climate change heightening fire hazards (Westerling 2006, Dicus 2009), social reluctance to modify residential landscaping (Dicus and Scott 2006), lax enforcement of defensible space laws (Dicus et al. 2009), and others. Nowhere is this trend more apparent than in California. The steadily increasing trend of devastating WUI fires was initiated by the 1991 Oakland Hills fire, which killed 25 people, injured 150 others, destroyed 2,843 single-family dwellings and 437 apartment and condominium units, and caused an economic loss estimated at $1.5 billion (FEMA 1992). Since the 1991 Oakland Hills Fire, 23 more fires in California have burned 500 or more structures, including 14 that destroyed over 1,000 buildings (California Department of Forestry & Fire Protection 2020).

It is clear that mitigation reduces the risk of structural loss. For example, San Diego County adopted construction standards in 2001 and strengthened those codes in 2004; subsequently, the rates of home loss were significantly lower during the 2007 fire storms for structures built to the new code compared to older residences that were built before building standards were enacted (Leyshon 2015).

Strengthening (or in many places, simply implementing) WUI fire regulations is increasingly being looked at to reduce wildland fire losses. Unfortunately, the efficacy of such regulations is sometimes difficult to assess before actual fire events. Further, the regulations work only in so far as they are enforced.

Not surprisingly, the large number of WUI losses in California have led to the most stringent fire regulations in the United States. For example, to mitigate heat exposure to buildings, 30.48 m of vegetative “defensible space” is required around all structures in the State Responsibility Area (SRA), which is where the state has primary fire suppression responsibilities (Public Resource Code 4291). Further, to make buildings more ignition resistant, Chapter 7A of the California Fire Code (first enacted in 2008) dictates standards for materials and assembly for new construction in the SRA, including minimum standards for roofing, vents, exterior coverings, exterior windows and doors, decking, and accessory structures. Many other regulations (e.g., water storage and road standards) have also been enacted to aid in firefighter and residential response during a wildfire. These SRA standards are commonly increased in Local Responsibility Areas (LRA), where local jurisdictions have primary fire suppression responsibilities.

Unfortunately, the actual effectiveness of specific elements in existing WUI fire regulations at reducing losses during wildfires is largely anecdotal. Part of the unknown stems from performance testing being conducted in a controlled laboratory setting that focuses on materials and/or assembly of individual elements of a building. During a wildfire, there is simply much greater variability in conditions that could lead to structural ignition, which cannot be accounted for in a laboratory setting that commonly isolates a single building element. For example, during a wildfire, a building component could simultaneously be exposed to an ember storm, intense radiant or convective heat, and direct flame impingement. Obviously, one cannot create an experiment where local communities are subjected to a large, high-intensity wildfire, but researchers can quantify the relative importance of structural and property features following a wildfire and assess the relative effectiveness of these traits on home survivability.

To that end, this study focuses on how various physical traits of a given property impacted the survivability of structures during the first 48 hours of the 2017 Thomas Fire in Ventura and Santa Barbara Counties in California (Figure 10). The Thomas Fire, which was driven by strong Santa Ana winds in largely chaparral shrublands, destroyed 1,063 structures, caused two fatalities, cost over $200 million to suppress (California Department of Forestry & Fire Protection 2017b) and caused over $1.8 billion in insurable losses (Ding 2018). Further exacerbating the destruction there, post-fire mudslides (a common secondary disaster that follows wildfires in California) occurred within weeks of full fire containment, killing 21 people and destroying over 400 dwellings that were spared during the actual wildfire.

Figure 10 Location of the 2017 Thomas Fire in Ventura and Santa Barbara Counties, California.

This research, which seeks to provide quantifiable evidence of the effectiveness of various property traits on structural survivability, is intended to better inform policymakers (and residents) so that they can more effectively mitigate wildland fire hazards and thereby reduce the cycle of repetitive wildfire costs and losses in the wildland-urban interface.

4.2. Methodology

4.2.1. Site Description

Of the 1,063 structures destroyed in the Thomas Fire, 803 were single-family homes and are the focus of this study. The extent to which outbuildings and auxiliary structures meet building requirements is inconsistent, and accurate data collection is challenging. For this reason, we focused on habitable, single-family homes, which made up the bulk of the destruction.

The study area consisted of a region of the 113,970 ha of the final Thomas Fire footprint, which was chosen because it reflected the initial stages of the fire, when wind speeds were extreme and suppression forces were limited. A sample of 222 destroyed single-family homes within a WUI interface community in the city of Ventura was selected as the study area (Figure 11). The specific rationale for the building selection process will be discussed in the statistical analysis section that follows. The study area consisted of homes that burned in the first 48 hours of the Thomas Fire under extreme weather conditions.

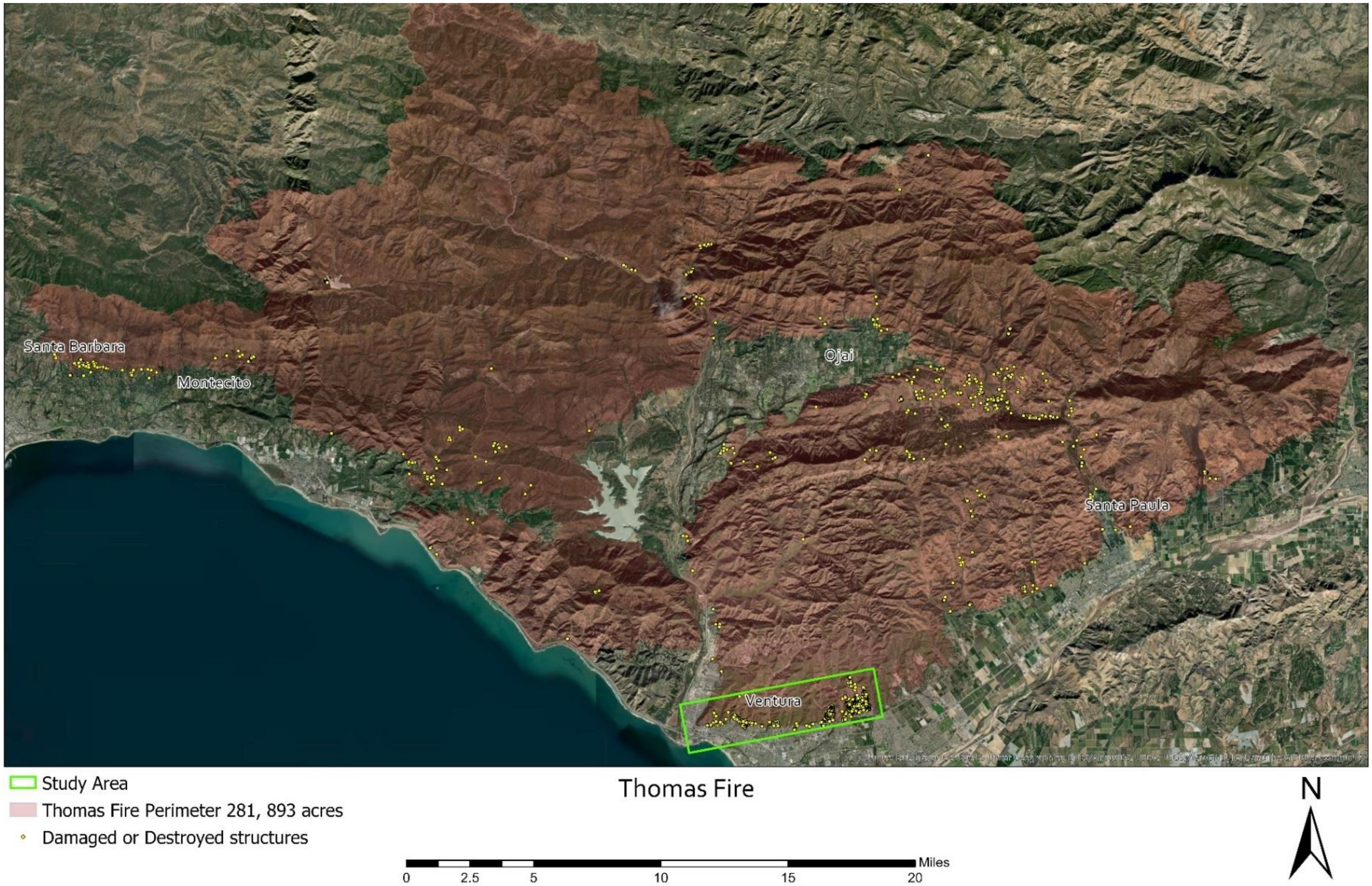


Figure 11 Final Thomas Fire footprint with the specific study area outlined by the green rectangle.

4.2.2. Data Sources

Initially, we intended to explore how structural survivability was influenced by a myriad of property features, including the degree of defensible space on a given property, specific building components (especially those that are addressed in Chapter 7A of the California Building Code), fire behavior at the time of fire passage, presence of suppression resources, and others. Unfortunately, much of the desired data proved impossible to acquire.

For example, numerous studies have shown that the type of windows, roofs, eaves, and siding plays a vital role in protecting a homes against wildfire (Hakes et al., 2017; Syphard et al., 2017). We had originally hoped to utilize the Damage Inspection (DINS) report that was produced by the State (which provides information on these and other property attributes) for these data on specific residences. Unfortunately, most of the values in the Thomas Fire DINS report were either blank or were considered unreliable. Thus, the Thomas Fire DINS report was largely used for simply determining the type of structure on a given damaged property (e.g., single-family residence, commercial, etc.) and the extent of damage that the building incurred (e.g., Superficial to Destroyed), which was based upon the percentage of the building damaged. Further, all homes included in the study were built circa 1975, well before Chapter 7A building codes were enacted in 2008, and thus it was impossible to determine if the current construction standards impacted structural survivability.

As a further means to gain data on building attributes at the time of the Thomas Fire, we also attempted to utilize pertinent building data from Zillow, which is an online real estate database company that collects data on homes throughout the US. Zillow maintains data about construction materials for given residences, but they only publicly provide data for homes that are actively on the real estate market; a request to Zillow for data for the study was denied. Further attempts to retrieve construction data from the Ventura County assessor's office were made; however, their office only maintains basic data, such as square footage and lot size, and does not have data on building materials used or upgrades. Thus, without a baseline of standards or reliable building information, the impact of home construction attributes on home survivability was impossible to assess.

Additional attempts to assess features that could potentially influence structural survivability also proved fruitless. For example, heat exposure at time of fire passage on a given property (which could potentially be reconstructed via fire behavior modeling) could not be determined due to limited knowledge of the specific timing of fire progression in the early stages of the fire. Similarly, it proved impossible to determine if suppression resources took defensive action on a given residence when the property was exposed to heat and embers.

We also purposefully chose not to assess how the topographic slope on which a given structure was located as a factor in structural survivability because the Thomas Fire ignited and initially spread under an extreme foehn (Santa Ana) wind event. Foehn winds dominate fire behavior and override local, diurnal wind patterns. ("Estimating Winds for Fire Behavior | NWCG," n.d.). Local topographic features that generally affect fire behavior in predictable patterns are inconsistent under foehn wind conditions, and commonly exhibit little difference in wind speed between day and night (Brinkman, n.d.).

Because of multiple unexpected data challenges, we were therefore limited to only assessing how building survivability was impacted by the type of vegetation and the degree of defensible space (in increasing distances from a given building footprint), and the presence and type of fencing on a given property.

Spatial data collection for this study came from numerous governmental and digital sources (Table 5). Visual inspection using satellite imagery was used to improve the accuracy of some spatial data. For example, pre-fire visual assessment utilizing Google Earth imagery (“Google Earth Pro,” 2019) and Google Street View (“Google,” 2011) revealed that much of the location data from the DINS report were inaccurate, in that point locations were not applied to specific rooftop locations. Cross-referencing through visual inspection with Google imagery was therefore used to assign each structure’s available attributes to its corresponding location, which was relegated to only the presence of a fence and whether it was combustible or non-combustible.

Because DINS reports only provides information about burned structures, data for unburned structures were acquired from county governmental organizations. The extent of the data varies from county to county. As such, it was difficult to obtain accurate and consistent data across jurisdictional boundaries.

Future post-fire investigations could be improved and expedited if a data clearinghouse was available for information relevant to post-fire analysis.

GIS Layers	Source	Content	Issues/Problems
Damage Inspection (DINS) points	County of Ventura Information Technology Services Department	Geographic point locations and associated building attributes for each structure damaged or destroyed as a result of the Thomas Fire.	Many point locations did not match home addresses. Missing structure data. Poor data collection.
Ventura County building footprints	Ventura County Assessor's Office	Building footprints for all structures within the Thomas Fire perimeter in Ventura county.	Ventura county only. Some footprints did not match actual building footprint. Many footprints needed to be adjusted to match imagery.
Santa Barbara Footprints	Microsoft Building Footprints	Building footprints for Santa Barbara County	Footprints required adjusting to match imagery. Many building footprints missing.
Ventura County Parcel data	Ventura County Assessor's Office	Parcels in Ventura County	N/A
Santa Barbara Parcel data	Santa Barbara Assessor's Office	Parcels in Santa Barbara County	N/A
Thomas Fire satellite imagery	The National Agriculture Imagery Program (NAIP)	Ventura and Santa Barbara imagery before the Thomas Fire	N/A
Thomas Fire Footprints	Environmental Systems Research Institute (ESRI)	Thomas Fire Perimeter polygon	N/A

Table 4 GIS Data Layers and Sources

4.2.3. . Spatial Data Processing

Imagery during 2016, which was obtained from the National Agriculture Imagery Program (NAIP), was used as a base map that allowed for the analysis of pre-fire landcover around structures (Figure 12). Because we needed to determine both the abundance and type of vegetation at a fine scale, pre-fire vegetation within the study site was determined using a supervised image classification technique utilizing ArcGIS Pro in conjunction with NAIP imagery at a 0.6-meter resolution (Figure 13).

Figure 12. Raw Imagery obtained from NAIP for a neighborhood in the study area.

Ventura County Information Technology Services Department provided shapefiles for point locations of damaged homes and building footprints for all homes in the area of interest. Unfortunately, many of the point locations proved inaccurate. Often addresses were incorrect, or structures were labeled as a primary residence when, in fact, they were outbuildings, which required extensive data editing. To accurately represent the structure location, building footprints were shifted and resized to fit the NAIP imagery.

Utilizing the 2016 NAIP imagery, the image classification wizard within ArcGIS Pro was used to create training samples of the desired vegetative classification categories. In this case, the intent was to distinguish different types of vegetation and development. Training samples were used to identify pixels in eight distinct classes: landscape vegetation, lawn, asphalt, concrete, developed, woodland, annual grasses, and wildland shrub.

LANDFIRE, a database of publicly available spatial data commonly used by land managers (Rollins, 2009), was considered for use in this study. However, the 30 m resolution was too large for individual parcel analysis and the vegetative classifications at the site consisted of only two classifications, including “non-burnable” and “shrub”. Figures 13 and 14 illustrate the difference utilization of NAIP and LANDFIRE data, respectively.

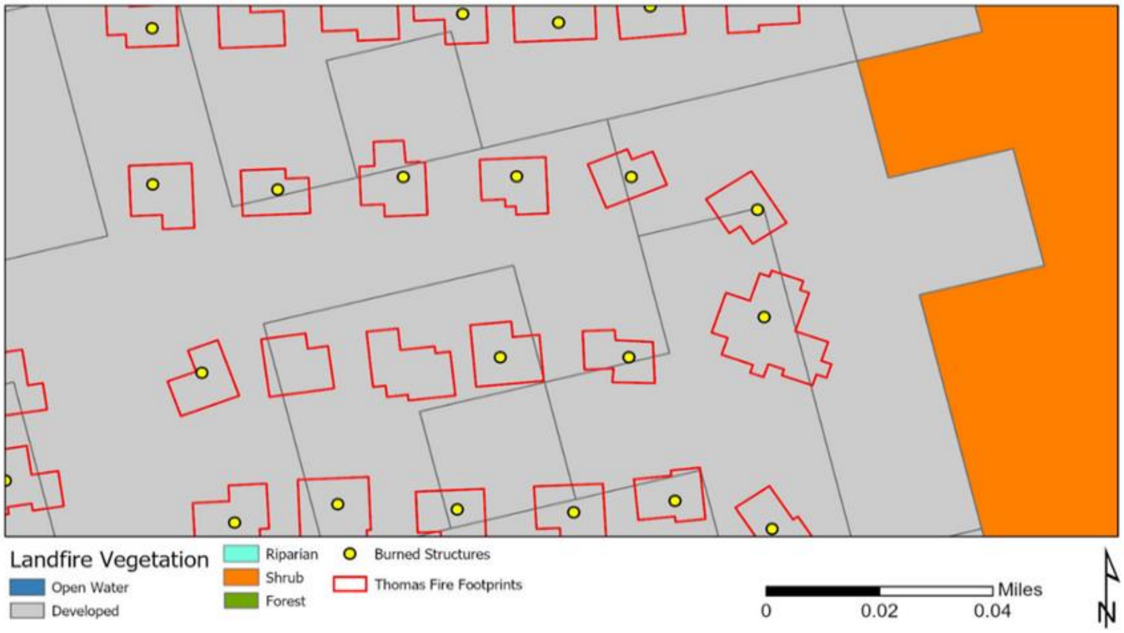


Figure 13 Vegetation Classification using LANDFIRE Data at 30m Resolution.

Note the grey area is classified as “non-burnable.” Most structures destroyed from the Thomas Fire were in non-burnable areas.

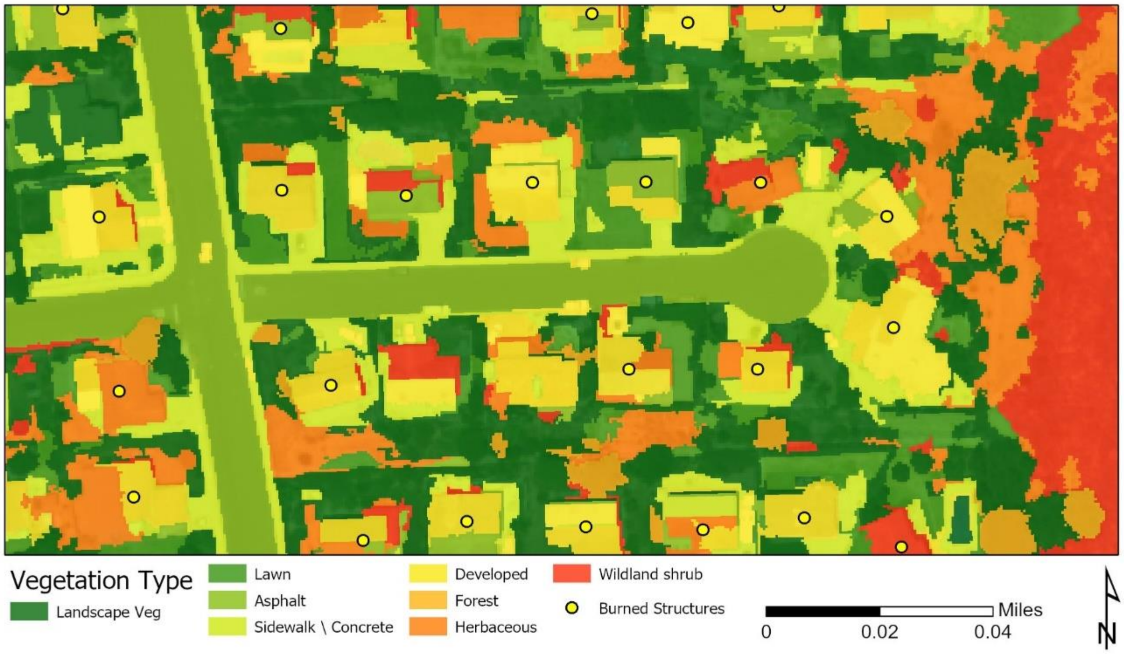


Figure 14 Vegetation Classification using ArcGIS Pro at 0.6m Resolution.

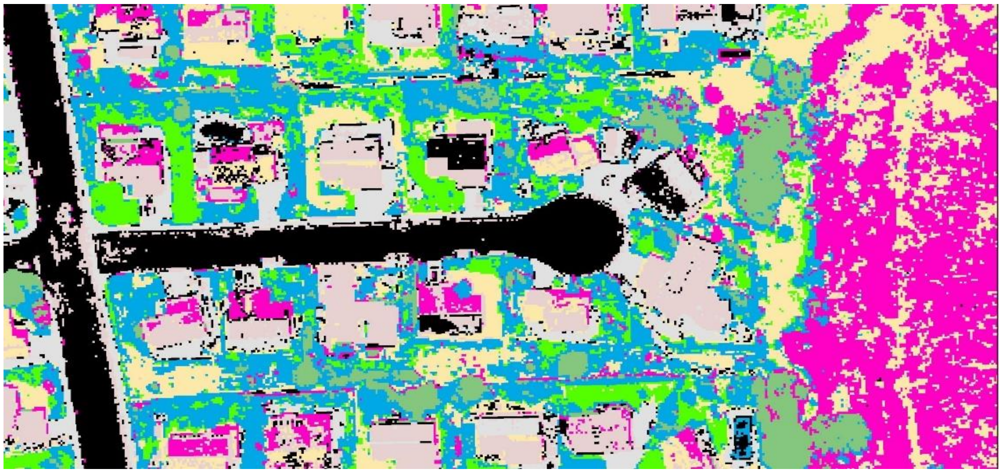
(“ArcGIS Pro | 2D and 3D GIS Mapping Software,” n.d.)

Fire behavior can vary dramatically based on different fuel types and associated moisture and chemical components. Classification categories with similar expected fire behavior were grouped together in the final analysis. Asphalt and concrete were grouped together in the final analysis as a “non-burnable” category. Lawn and landscape vegetation classifications are based on irrigated, green vegetation with high moisture content. These categories were grouped together as “landscape vegetation” due to similar expected fire activity.

Classification types included in the final analysis are defined as follows:

- Landscape Vegetation- Irrigated, ornamental grasses, shrubs, and forbs with high foliar moisture.
- Non-Burnable- Asphalt road surfaces and concrete infrastructure
- Developed- Housing units and structures
- Woodland- Native oaks and hardwoods
- Annual Grasses- Non irrigated, native or invasive, annual wild grasses
- Wildland Shrub- Chapparal and coastal sage scrub plant communities

We conducted a Supervised Image Classification with an object-based classification using training samples and the 4-band NAIP imagery. The output raster was further generalized using the generalization tools outlined within ArcGIS Pro. The initial raster output was pixelated and misclassified some vegetation. Training samples using visual observation were created to “smooth” the data and classify the final raster. The workflow of converting the initial raster classification to the final raster output raster is illustrated in Figure 15. The raster output from the original image classification step was then converted to polygons using the Raster to Polygon spatial analyst tool to represent the eight classified landcover groups of interest.



Initial output raster after classification

↓

Remove misclassified cells with Majority Filter

↓

Repeat Majority Filter

↓

Identify clusters with Region Group

↓

Remove areas smaller than a threshold

↓

Eliminate small regions with Nibble

↓

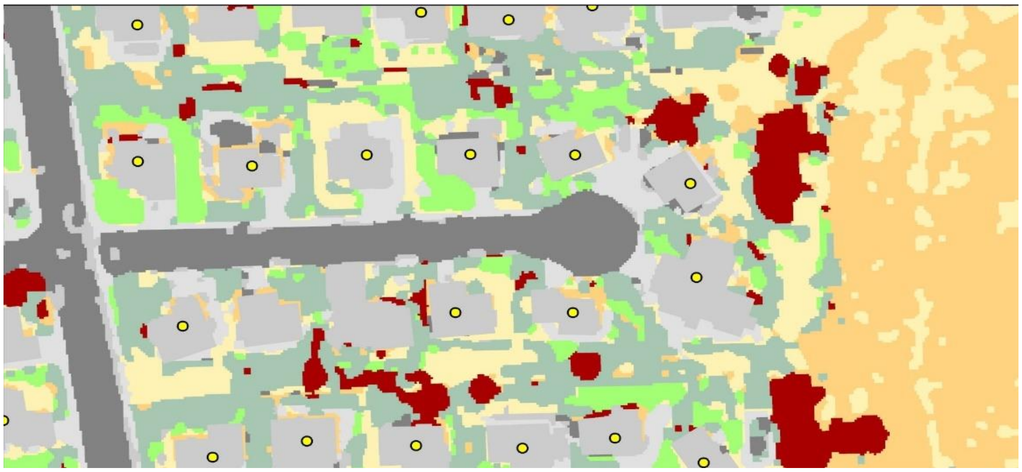


Figure 15 Classification of Locations

Three buffer zones of increasing distance from around the footprint for each of the 444 selected homes in the study. We used the Multi-Ring Buffer tool in ArcGIS Pro to create these buffers at the specified distances below (Figure 16). These zones are based on NFPA and are also similar to defensible space zones categorized within California Public Resources Code 4291, which are a group of State regulations intended to reduce home ignition during a wildfire.

The specific zones include:

- Zone -A: 0 m – 1.5 m Immediate zone
- Zone -B: 1.5 m – 9 m Intermediate zone

Zone – C: 9 m – 30 m Extended zone

Figure 16 Buffer zones of increasing size (0 - 1.5 m, 1.5 m – 9 m and 9- 30 m) around houses included in the analysis.

We calculated the percentage of each of the 6 land cover types in each of the 3 buffer zones around each structure. These summary statistics were then used to form the basis of the logistical regression model during the statistical analysis phase.

4.2.4. Statistical Analysis

I utilized a matched pair statistical technique in this study. This approach is an observational study technique that evaluates the effect of a treatment (in this case, wildfire) by comparing adjacent burned and unburned homes (Figure 17) that share many similar characteristics (via a visual assessment of lot size, house age, landscaping, etc.) (Stuart, 2010). Our strategy was to choose homes that had sustained major damage (51-75%) or that were destroyed (>75%) as categorized in the Thomas Fire DINS report. We chose to focus on single-family residences that had sustained major damage because they offered the most consistent and accurate data in the DINS report. Of the total 1,063 structures that sustained major damage (i.e., 51-75% damage) or were destroyed (i.e., >75% damage) during the Thomas Fire, 699 single-family residences met the damage criteria.

Figure 17 Example of paired homes for analysis

The specific study area within the Thomas Fire footprint (Figure 11) was chosen because that geographic area had the highest degree of home loss that occurred during similar weather conditions, and also had the greatest opportunity to find burned/unburned home pairs (508 of the total 699 burned, single-family homes that met the damage criteria are within the specific study area). These buildings sustained damage during the first 48 hours of The Thomas Fire, when Santa Ana wind conditions were extreme and fire response was limited. Of the 508 homes that met the damage criteria within the study area, a subsample of 222 damaged or destroyed homes were selected because they were located immediately adjacent to an unburned home. The neighboring properties were then analyzed using the matched pair statistical technique for vegetation type and for presence/type of fencing.

The paired analysis controls for confounding variables that may have been present during the fire, such as differing wind conditions or presence of suppression resources. Paired houses are considered to share similar attributes (i.e., home age, lot size, square footage, etc.) and to have been influenced by the same weather conditions. The study area consists of tract homes that were all built circa 1975 and the average lot size is 0.3 acres. The study area is an example of a traditional WUI interface community where there is a distinct border between urban development and wildland vegetation. Due to relatively small parcel size, neighboring properties share a similar physical setting.

We conducted a binary logistical regression model using SPSS software (“SPSS Software | IBM,” 2013) to examine the relationship between property features and home survival. Initial explanatory variables that were included in the logistical regression model included the percentage of a specific land cover (i.e., developed, wildland shrub, woodland, landscape vegetation, grasses, and non-burnable) within each of the three increasing buffer zones around each structure (i.e., 0-1.5 m, 1.5-9.0 m, and 9.0-30.0 m). Fence type (i.e., combustible, non-combustible, and none) was also included in the logistic regression model.

A stepwise selection technique was used to reduce the logistic regression model to identify variables of statistical significance at $\alpha = 0.05$. Stepwise selection is a process by which the model initially includes all available variables, and then systematically removes the least important factors until only those variables with statistical significance are left in the final model.

4.3. Results

For each of the three increasing buffer zones around a house (i.e., 0-1.5 m, 1.5-9.0 m, and 9.0-30.0 m), coefficients of specific variables utilized in the logistical regression model and their statistical significance follow. Nomenclature for the percentage of a given land cover type that occupied a given buffer zone is “Pct_(Cover Type)_(Buffer Size)”. Thus, the percentage of the 1.5 m buffer that was occupied by the Non-burnable land cover type would be “Pct_Non-Burnable_1.5”.

4.3.1. Zone A: 0.0-1.5 m Around a Home

A Chi-square test (Table 5) showed that the logistical regression model developed for the 0.0-1.5 m buffer zone was a significant predictor of whether a home burned or not ($\chi^2 = 30.810$, $p < .001$). The calculated Nagelkerke Pseudo R^2 indicated that the model accounted for 8.9% of the total observed variance.

In the 1.5-meter (~5 feet) buffer zone, the percentage occupied by the “non-burnable” (asphalt and concrete) cover type and the presence of a non-combustible fence were significant predictors in determining structural survivability during the Thomas Fire ($\alpha = 0.05$; Table 6). No other land cover type was statistically significant. Within this zone closest to a house, each percentage point increase of “non-burnable” landscaping increased the odds of a house surviving by 1680% ($p = 0.033$). Also, within the 1.5 m buffer, the presence of a non-combustible fence increased the odds of a home survivability by 280%.

Table 5 Omnibus Tests of Model Coefficients at 1.5m

	Chi-	df	p
Step	30.810	8	<0.001
Block	30.810	8	<0.001
Model	30.810	8	<0.001

Table 6 Logistic Regression of house survivability in the buffer zone 1.5 meters around a home (N=444).

Effects	**B**	**SE**	**Exp (B)**	**LL**	**UL**	***p***
Constant	-3.38		0.03			0.011
Fencing						0.000
None	0.38	.48	1.47	0.58	3.74	0.422
Combustible	0.48	0.44	1.61	0.68	3.84	0.279
Non-Combustible	1.34	0.43	3.80	1.64	8.81	0.002
Pct_Landscape_1.5	2.90	1.54	18.18	0.88	374.32	0.060
Pct_Non_Burnable_1.5	2.88	1.35	17.81	1.27	250.66	0.033
Pct_Developed_1.5	2.31	1.41	10.10	0.64	160.40	0.101
Pct_Woodland_1.5	1.42	2.45	4.15	0.03	503.91	0.561
Pct_Grasses_1.5	2.88	1.60	17.75	0.78	406.23	0.072

4.3.2. Zone B: 1.5-9.0 m Around a Home

A Chi-square test (Table 7) showed that the logistical regression model developed for the 1.5-9.0 m buffer zone was a significant predictor of whether a home burned or not (χ^2=34.933, p<0.001). The calculated Nagelkerke Pseudo R^2 indicated that the model accounted for 10.1% of the total observed variance.

In the 1.5-9.0-meter (~5-30 feet) buffer zone, no land cover type was a significant predictor in home survivability during the Thomas Fire (α = 0.05; Table 8). However, the presence of a non-combustible fence within the 9m buffer zone was significant (*p*=0.002) and increased the odds of home survivability by 280%.

Table 7 Omnibus Tests of Model Coefficients at 9m

	Chi-Square	df	p
Step	34.933	8	.000
Block	34.933	8	.000
Model	34.933	8	.000

Table 8 Logistic Regression of house survivability in the buffer zone 1.5-9.0 meters around a home (N=444).

Effects	**B**	**SE**	**Exp (B)**	**LL**	**UL**	***p***
Constant	-5.462		0.004			0.085
Fencing						0.000
None	0.27	.48	1.31	0.51	3.40	0.575
Combustible	0.44	0.44	1.60	0.66	3.70	0.314
Non-Combustible	1.40	0.43	3.90	1.70	9.10	0.002
Pct_Landscape_9	4.90	3.30	133.15	0.22	79664.22	0.134
Pct_Non_Burnable_9	5.68	3.20	264.28	.48	145420.81	0.083
Pct_Developed_9	2.50	3.51	12.31	0.01	11875.24	0.474
Pct_Woodland_9	3.90	4.00	51.00	0.02	118995.20	0.321
Pct_Grasses_9	4.50	3.40	86.80	0.11	67798.90	0.189

4.3.3. Zone C: 9.0-30.0 m Around a Home

A Chi-square test (Table 9) showed that the logistical regression model developed for the 9.0-30.0 m buffer zone was a significant predictor of whether a home burned or not ($\chi^2=43.913$, $p<0.001$). The calculated Nagelkerke Pseudo R^2 indicated that the model accounted for 12.6% of the total observed variance.

In the 9.0-30.0-meter (~30-100 feet) buffer zone, the percentage occupied by "non-burnable" land cover type, the percentage occupied by the "landscape vegetation", and the presence of a non-combustible fence type were significant predictors in determining structural survivability during the Thomas Fire ($\alpha = 0.05$; Table 10). Within this zone farthest from a house, each percentage increase of "Non-Burnable" cover type increased the odds of house survivability by 165,566%. Additionally, each percentage increase of "Landscape Vegetation" cover type increases the odds of a house not burning by 275,594%. Finally, the presence of a non-combustible fence increased the odds of a home not burning by 260%

Table 9 Omnibus Tests of Model Coefficients at 30m

	Chi-Square	df	p
Step	43.913	8	.000
Block	43.913	8	.000
Model	43.913	8	.000

Table 10 Logistic Regression of house survivability in the buffer zone 9.0-30.0 meters around a home (N=444).

Effects	B	SE	Exp (B)	LL	UL	*p*
Constant	-6.871		0.001			0.060
Fencing						0.000
None	0.14	.49	1.15	0.44	3.00	0.772
Combustible	0.32	0.46	1.40	0.56	3.40	0.480
Non-Combustible	1.28	0.44	3.60	1.53	8.50	0.003
Pct_Landscape_30	7.92	3.83	2755.944	1.53	4977565.00	0.038
Pct_Non_Burnable_30	7.41	3.86	1655.674	1.10	2609494.00	0.048
Pct_Developed_30	2.91	3.91	18.33	0.01	38977.90	0.457
Pct_Woodland_30	3.00	4.60	19.38	0.00	153751.24	0.518
Pct_Grasses_30	6.42	4.20	612.60	0.17	2153649.00	0.123

4.3.4. All Zones: 0.0-30.0 m Around a Home

When all three buffer zones were combined into a single buffer, a Chi-square test (Table 11) showed that the logistical regression model developed for the 0.0-100.0 m buffer zone was a significant predictor of whether a home burned or not (χ^2=43.326, *p*<0.001). The calculated Nagelkerke Pseudo R^2 indicated that the model accounted for 14.0% of the total observed variance.

In the combined 0.0-30.0-meter (~0-100 feet) buffer zone, no land cover type was a significant predictor in home survivability during the Thomas Fire ($\alpha = 0.05$; Table 12). However, the presence of a non-combustible fence in the combined buffer zone was significant (*p*=0.003) and increased the odds of home survivability by 280%. ($\alpha = 0.05$; Table 4.7). Within this zone farthest from a house, each percentage increase of "Non-Burnable" cover type increased the odds of house survivability by 273%.

Table 11 Omnibus Tests of Model Coefficients including all variables

	Chi-Square	**df**	**p**
Step	49.326	18	.000
Block	49.326	18	.000
Model	49.326	18	.000

Table 12 Logistic Regression on whether a house burned or not including all variables at all distances (N=444)

Effects	**B**	**SE**	**Exp (B)**	**LL**	**UL**	***p***
Constant	-8.984		0.000			0.045
Fencing						0.000
None	0.14	.49	1.15	0.44	3.03	0.774
Combustible	0.34	0.47	1.41	0.56	3.53	0.466
Non-Combustible	1.32	0.45	3.73	1.55	8.50	0.003
Pct_Landscape_1.5	3.05	1.84	21.20	.57	8.99	0.097
Pct_Non_Burnable_1.5	2.44	1.58	11.47	.52	783.97	0.123
Pct_Developed_1.5	2.30	1.96	9.94	.40	254.02	0.162
Pct_Woodland_1.5	2.76	.72	15.83	.03	247.92	0.396
Pct_Grasses_1.5	3.01	2.43	20.29	.46	9294.26	0.119
Pct_WildlandSh_1.5						
Pct_Landscape_9	-.12	.001	.88	.00	1903.84	0.975
Pct_Non_Burnable_9	.67	.030	1.96	.00	3782.46	0.862
Pct_Developed_9	-1.32	.098	.27	.00	1012.03	0.754
Pct_Woodland_9	.79	.027	2.20	.00	27723.37	0.870
Pct_Grasses_9	-.28	.01	.76	.00	2348.235	0.945
Pct_WildlandSh_9						
Pct_Landscape_30	7.40	3.97	1641.37	.66	4055222.45	0.063
Pct_Non_Burnable_30	6.83	3.92	921.04	.42	2012248.84	0.082
Pct_Developed_30	2.96	4.08	19.268	0.01	56925.46	0.468
Pct_Woodland_30	2.54	4.74	12.64	0.00	137942.46	0.593
Pct_Grasses_30	6.07	4.35	430.70	0.09	2177987.44	0.163
Pct_WildlandSh_30						

4.4. Discussion

4.4.1. Relevant Findings

The most consistent predictor of structural survivability within the study area was the presence of a non-combustible fence. California has some of the strictest building guidelines in the US for homes built in the WUI. However, the use of noncombustible fences has been widely ignored or simply suggested as a recommendation rather than an enforceable regulation. We found that the odds of home survival increased dramatically if a noncombustible fence was present on a given property.

Unfortunately, some recently devastated communities continue to attach combustible fences to newly built homes, thereby placing the structure at future risk even if the newly built home is compliant to Chapter 7A standards. Thus, the negative impact of combustible fencing on structural survivability should be emphasized when fire management professionals engage with residents about wildfire risk reduction strategies.

We found that the type of fence attached to a structure (i.e., combustible vs. non-combustible) was a more significant predictor of home survivability than defensible space. This does not suggest that defensible space is ineffective or should be ignored. Indeed, we found that irrigated landscaping within the 30m buffer zone and non-burnable landcover in both the 1.5m and 30m zones is significant at promoting structural survivability.

Within the 1.5m buffer zone, we found that the non-burnable cover type (i.e., concrete, gravel, etc.) significantly increased the potential for home survival. This finding is significant because many residents commonly place combustible mulch or vegetation immediately next to the home. This study reinforces previous studies (Brzuszek &

Walker, 2008; Syphard et al., 2017)that found that combustible material of any type should be avoided immediately next to a given home. Smoldering embers can linger in combustible materials well after the initial fire front passes, and a home can readily ignite after suppression resources have relocated to other parts of the fire.

We also found that within the 30m buffer zone around a given house (the State-mandated zone for defensible space implementation), increasing presence of irrigated landscape vegetation and non-burnable land cover types around a home substantially improved the probability its survivability, even in the older homes that were exposed to the early stages of the Thomas Fire when winds were extreme and suppression resources were limited.

Unfortunately, many WUI communities have high-density housing, and residents living there rarely have control of factors 30m or, even at times, 3m from their homes due to relatively small property sizes. Defensible space policies generally only require compliance up to the property line regardless of the conditions on the neighboring property. This characteristic of small property size in relationship to current defensible space regulations clearly illustrates the need for community-level mitigation policies (vs. current parcel-level policies) to best reduce wildfire risk in a given community.

Initially, the overarching goal of this study was to evaluate how a myriad of pertinent physical variables impacted home loss during a wildfire, but there were multiple data limitations that impacted the robustness of the analysis in this study. First, as noted, the Thomas Fire DINS report contained numerous missing and incorrect data, including address locations and extent of damage at a given property. For example, Google Earth imagery revealed that some destroyed homes were not listed as such in the DINS report.

Similarly, while the standard DINS report template includes potential inputs for eaves, roof type, exterior siding, window type, and accessory structures on a given property, most of these values were null in the Thomas Fire DINS report. The prevalence of both incomplete and inaccurate data highlights the need for improved data literacy and training for those tasked with post-fire damage inspection.

As noted, lack of other relevant data (e.g., site-specific weather, fire behavior, suppression actions, etc.) also limited our original vision of data analysis. To control for these and other confounding variables, we therefore elected to employ the matched pair statistical technique described in 4.2.4. In this type of analysis, we were forced to assume that pairs of adjacent, neighboring homes would have experienced mostly identical conditions at the time of fire exposure, which is impossible to unequivocally determine without direct measurement.

Caution should be taken in applying these results in situations outside the conditions present in our data. For example, the Thomas Fire burned in mostly chaparral fuels before entering into older developed neighborhoods (c. 1975) during an extreme Santa Ana wind event. Even if another fire burned in similar wildland fuels and winds, home survivability would likely differ in newly built, master-planned communities where mitigation has been employed at multiple scales. Even with these limitations, we are confident that agencies and residents can employ elements of this study to help guide and develop more effective mitigation strategies.

4.4.2. Management Implications & Future Research Needs

There is no doubt that statewide policies such as defensible space standards (Public Resources Code 4291) are associated with home survivability (Keeley & Syphard, 2019). However, the relative effectiveness of defensible space compared to other factors is dependent on site-specific conditions. Current efforts to mitigate the impacts of increased fire activity are not proving effective at preventing structure loss (Kramer et al., 2019). Traditional mitigation techniques have failed to yield positive results during extreme wind events such as the Santa Ana winds in which the Thomas Fire progressed in its early stages (Keeley & Syphard, 2019).

The Thomas Fire was not an anomaly. Thousands of structures have been annually destroyed by wildfire in recent years in California. As development continues to push further into wildland areas, the potential for further destruction is likely, especially if such development is conducted in a piecemeal way. The lack of effective mitigation strategies has resulted in increased structure loss, billions of suppression dollars spent, and frustration amongst residents.

Numerous studies (Hakes et al., 2017; Syphard et al., 2017) have addressed the impact of various property features on home survivability during a wildfire and some consensus has begun to emerge. Effective wildfire mitigation must rely on a suite of variables rather than individual characteristics of a given property. Initially, we planned to assess various construction and other features in the logistic regression model to predict home survivability. However, the lack of complete data proved this goal impossible, which highlights the need for improved data literacy skills for agency personnel tasked with conducting post-fire damage inspections. Furthermore, consistent, multi-agency training on how to properly conduct DINS assessments would improve the quality of data for future research.

We relied on a variety of county and state-level data sources (Table 4) to conduct this study. Gathering this data was a time-consuming process and often required communication with multiple sources within the same agency. Currently, differing type of data (DINS, parcel data, building footprints) are confined to individual agency departments. Thus, a centrally located GIS database would allow easier access for researchers in the future and ultimately lead to improved analysis of home survivability.

A more extensive study of all WUI events in California that considers building attributes and that assess vegetation profiles at a much finer scale would also improve the quality of the research and ultimately inform better mitigation policy. Furthermore, a review and consolidation of current mitigation policies and guidelines to determine their effectiveness will help residents make more informed decisions and take the appropriate measures for their property-specific needs.

4.4.3. Conclusions

This study provides insight into the relative effectiveness of mitigation policies and guidelines. We hope to provide homeowners with options to achieve realistic and effective mitigation strategies. While the focus of this study is one particular fire under extreme wind conditions, the results can be applied to communities across southern California that experience similar types of wind-driven fires.

This study reinforces the need for continued research into structural ignitions and the development of site-specific mitigation strategies. One-size-fits-all approaches, such as focusing exclusively on implementation of defensible space, do not address the myriad of factors at play during a wildfire. Agencies that solely advocate defensible space and fuel modification without addressing structural characteristics provide a disservice to the public. Homeowners of limited means could weigh whether they should focus on landscaping or installing a noncombustible fence. This study highlights a disconnect between large-scale, government-sponsored mitigation programs, and homeowners trying to achieve realistic risk reduction goals on their properties. Thus, mitigation efforts need to be tailored for individual community characteristics rather than on large scale, state, or federal templates.

Effective wildfire mitigation relies on multiple factors, and government agencies must take a holistic approach to reduce future structural ignitions. Mitigation programs that consider the dynamic nature of wildfire and its response to site-specific local conditions (both current and predicted) will help reduce future tragedies. While there are many current policies in place to reduce risk of home loss, residents are often confused by their language, agency enforcement is inconsistent, and strategies are sometimes based on “one size fits all” approaches that negates site-specific nuances of a given property.

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